Open heavy flavor measurements with PHENIX

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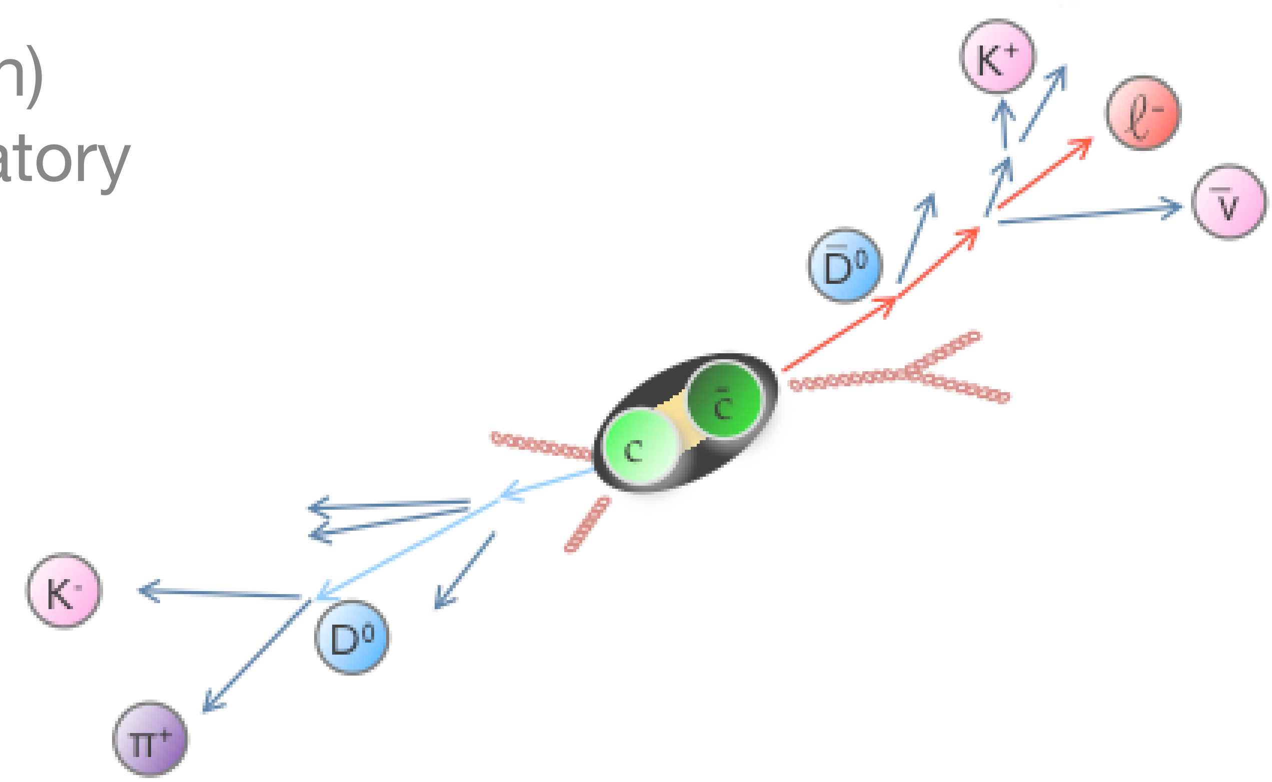


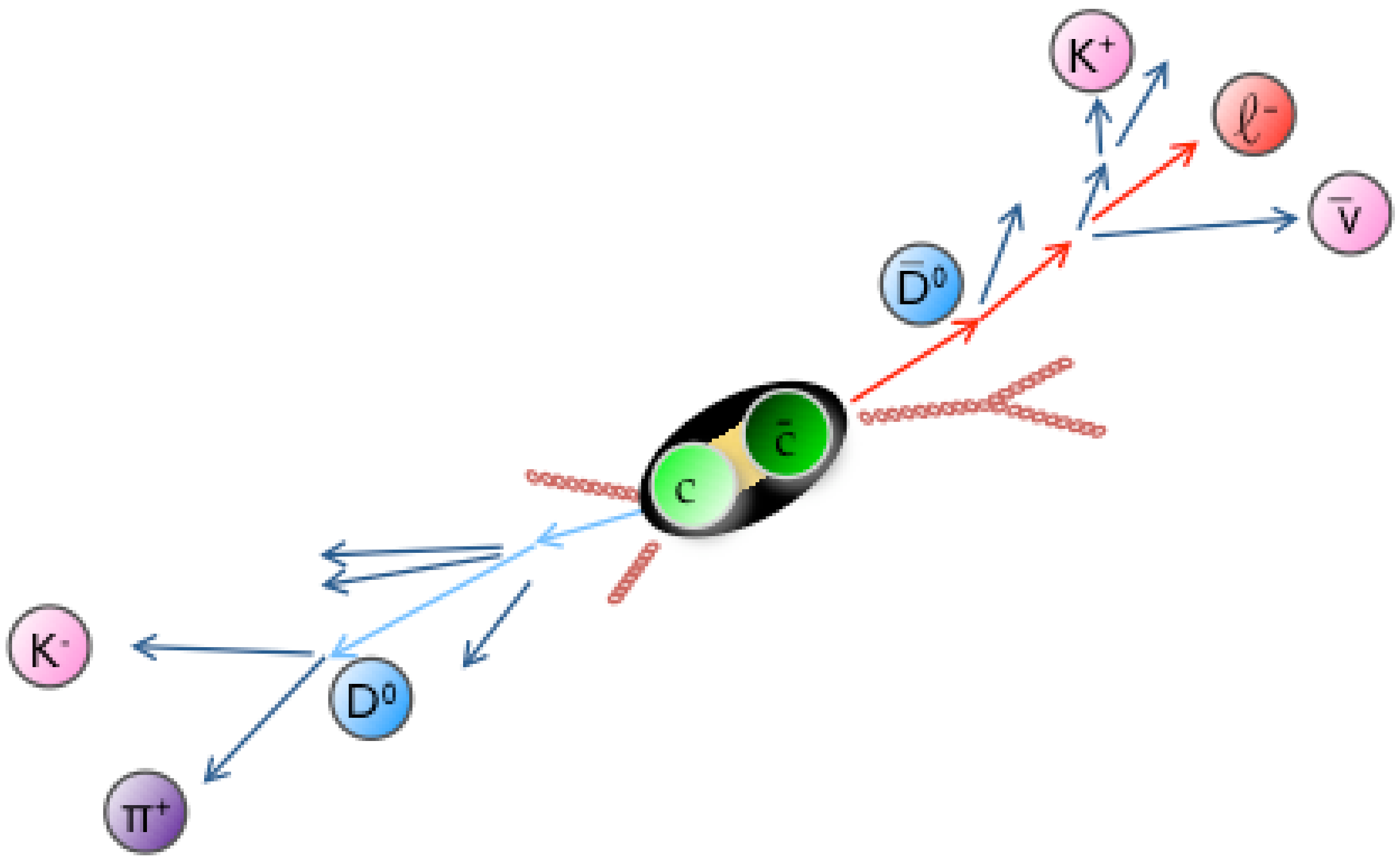
International Workshop on Heavy Quark Production in Heavy-ion Collisions,

PUDRUE University, January 4-6, 2011

Why study open heavy flavor in heavy ion collisions?

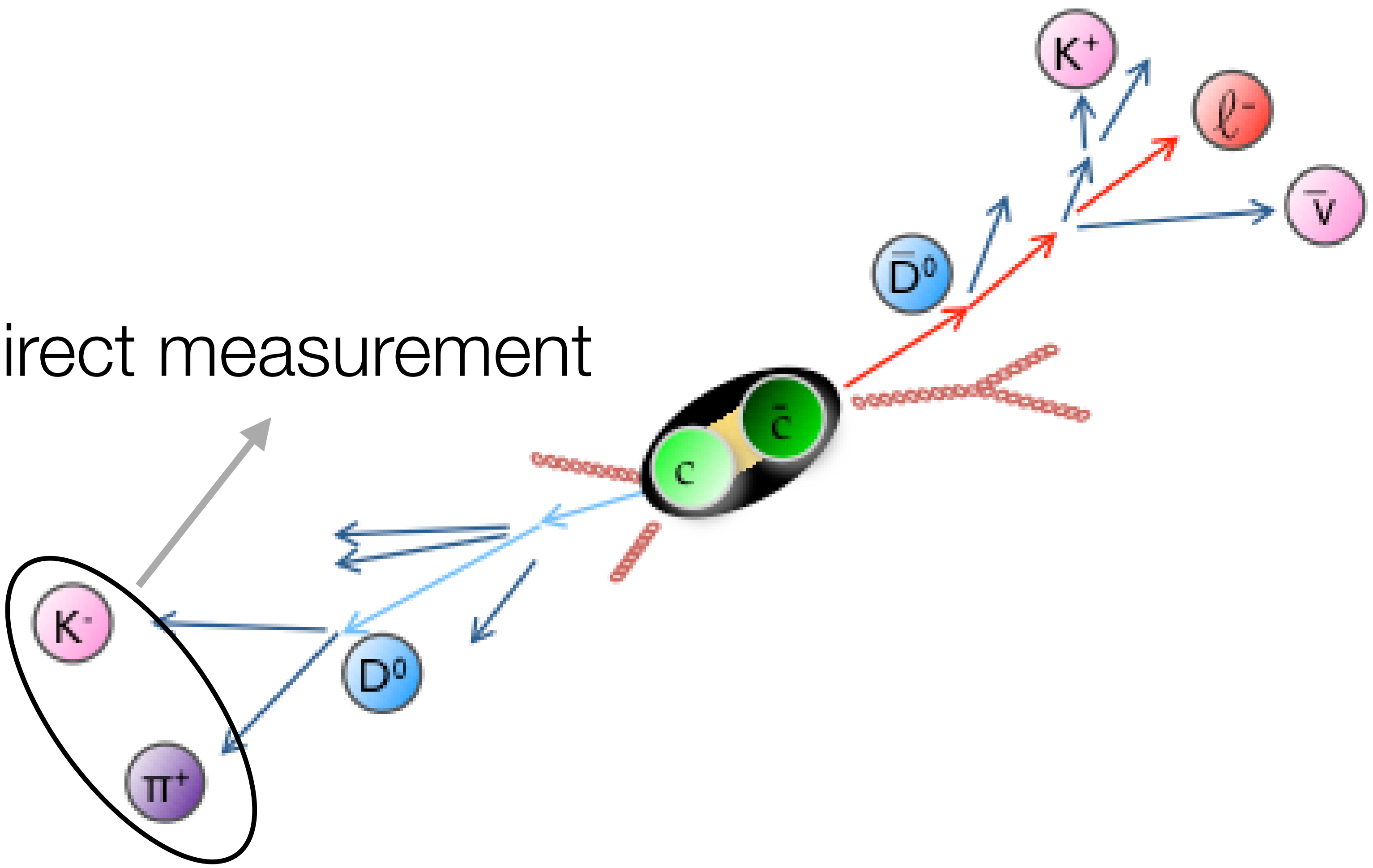
- Relatively large mass allowing to use pQCD framework (p+p collisions)
- Established as an important independent probe of the sQGP medium (initial and final energy loss)
- Important baseline measurement for better understanding heavy quarkonia production
- Total number produced heavy quarks expected to scale with number of binary nucleon-nucleon collisions
- Heavy quarks' coupling with medium much stronger than originally expected (large suppression and collectivity)

Measuring heavy quarks - Outline

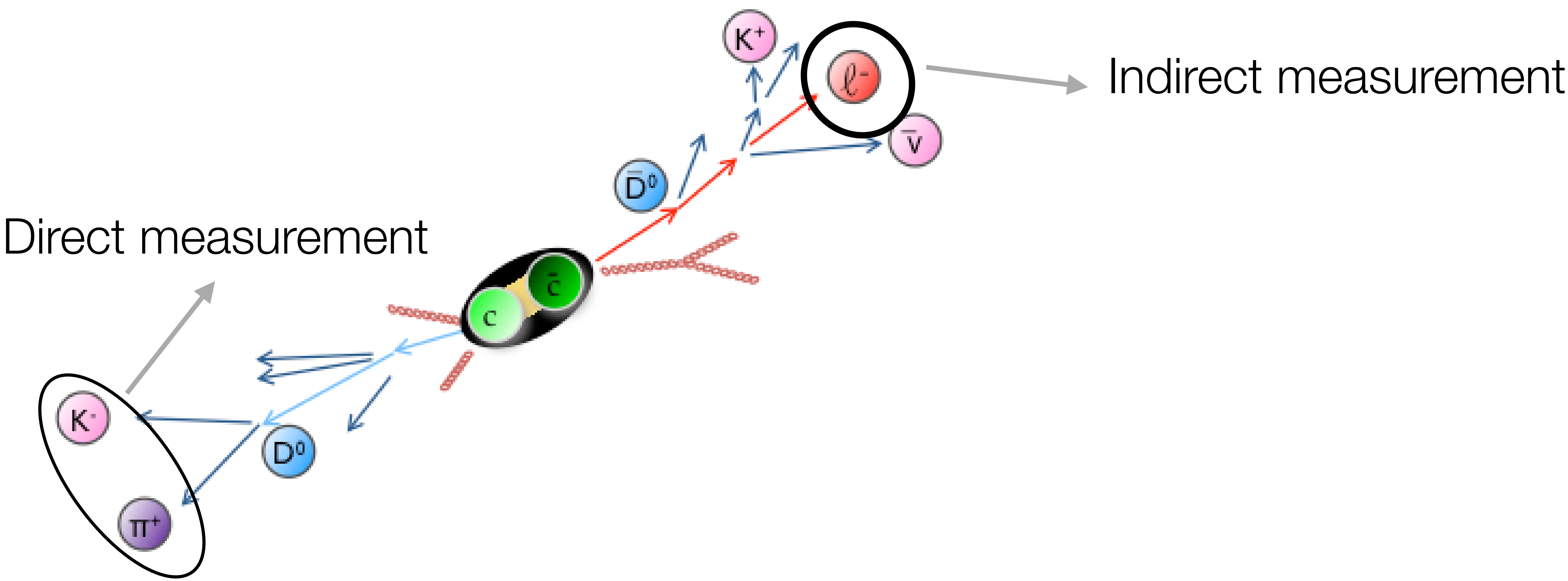


Measuring heavy quarks - Outline

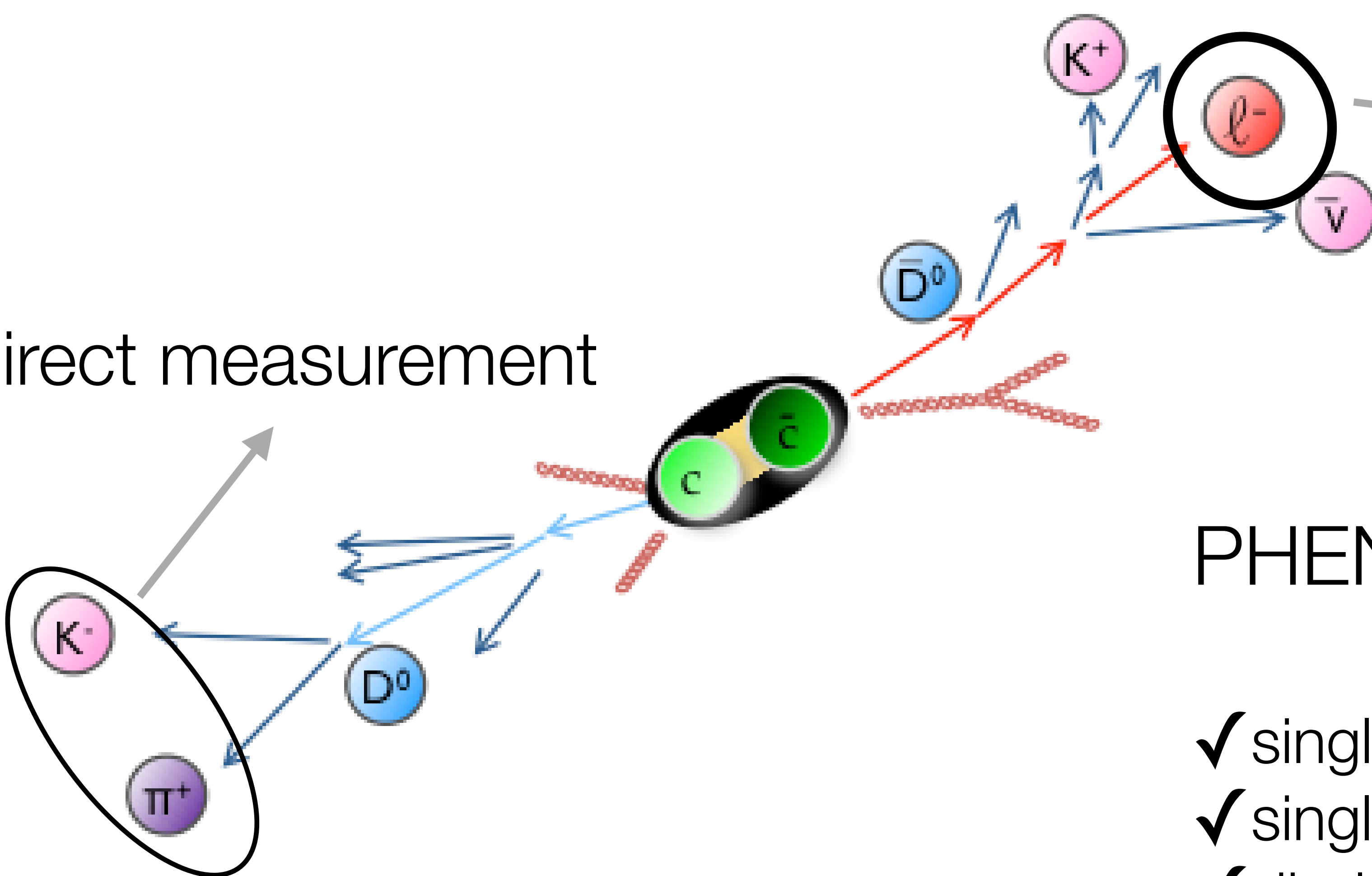
Direct measurement



Measuring heavy quarks - Outline



Measuring heavy quarks - Outline



Indirect measurement

Direct measurement

PHENIX measurements:

✓single electron
✓single muon
✓di-electron correlation
✓e-μ correlation

Detecting electrons with the PHENIX central arms

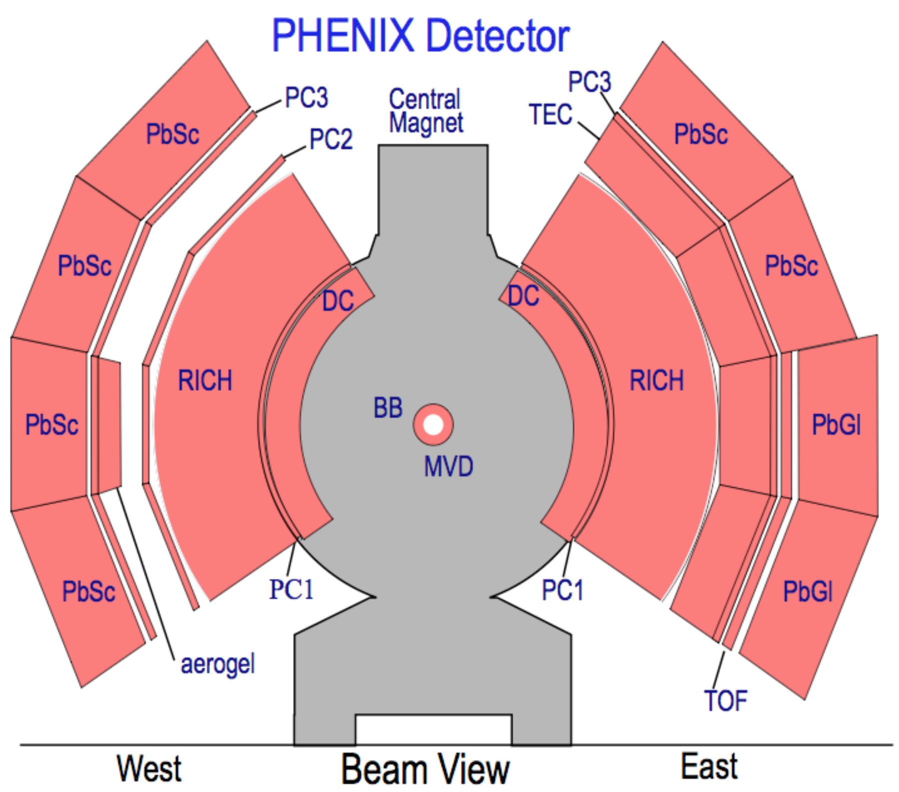
- Kinematic coverage:
  $\eta < 0.35$, $\Delta\varphi = 2 \cdot \pi/2$,
  $p_T > 0.2$ GeV/c

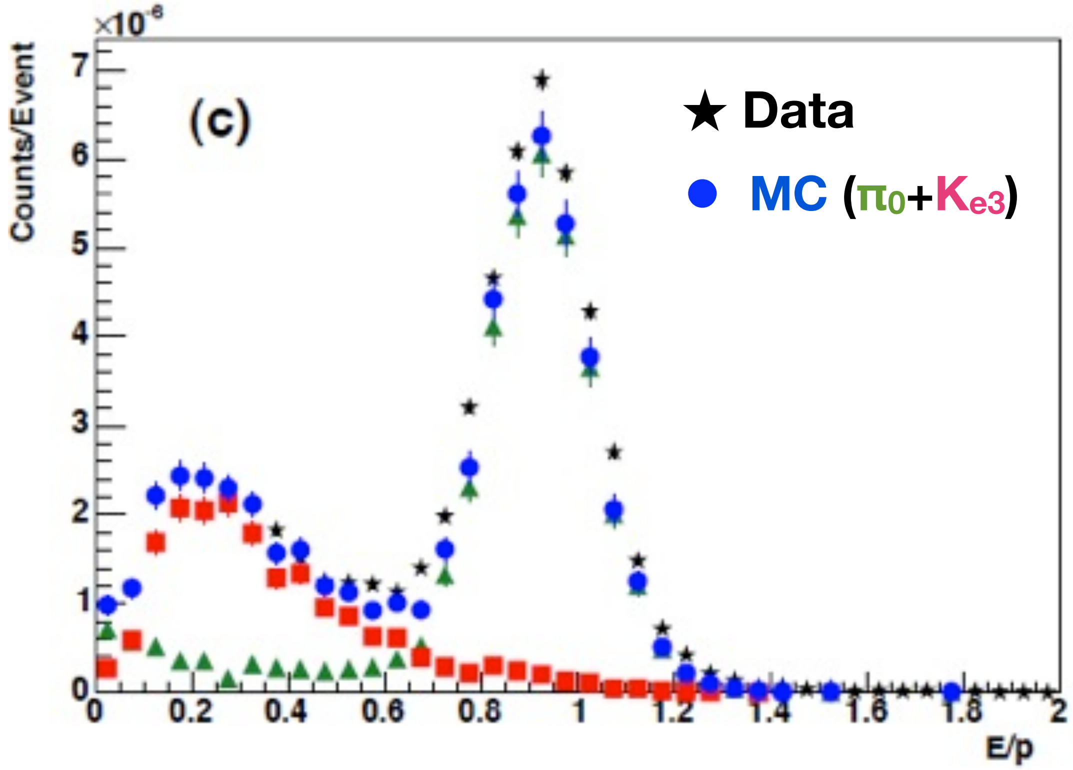
- DC, PC1 provide tracking

- RICH & EMCal provide very clean electron identification

- E/p ~ 1 for electrons

- **Small amount of detector material 0.4% X_0, i.e. small photonic background**





Sources of electrons: signal and background

Photonic electrons

- **Photon conversions**
  $\pi^0, \eta \rightarrow \gamma\,\gamma,$
  $\gamma \longrightarrow e^+ e^-$ in material
  Main background
- **Dalitz decays**
  $\pi^0, \eta \rightarrow \gamma\, e^+ e^-$
- **Direct Photon**
  Small but significant at high p_T
  Measured by PHENIX

Non-photonic electrons

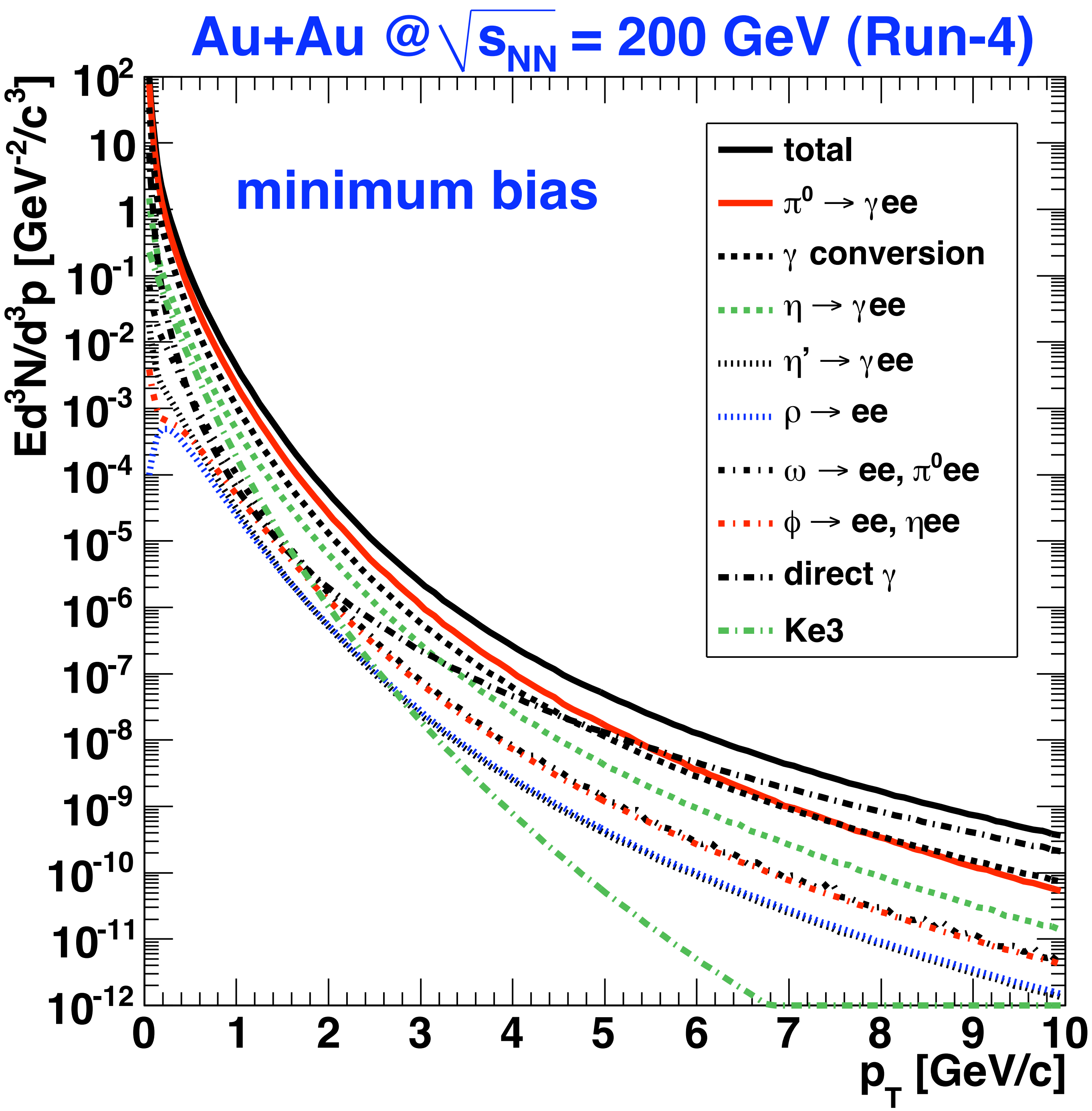
- **Heavy flavor electrons**
  $D \longrightarrow e^{\pm} + X$
- **Weak Kaon decays**
  K_{e3}: $K^{\pm} \rightarrow \pi^0\, e^{\pm}\, \nu_e$
  < 3% of non-photonic in p_T > 1.0 GeV/c
- **Vector Meson Decays**
  $\omega, \rho, \phi, J/\psi, \Upsilon \rightarrow e^+ e^-$
  < 2-3% of non-photonic in all p_T

Signal = Inclusive spectrum - Background

Background estimated with two separate Cocktail and Converter Methods

Cocktail method

- All background sources measured by PHENIX
- Used as the input for the “hadronic cocktail”
- Decay kinematics and photon conversions reconstructed by detector simulation

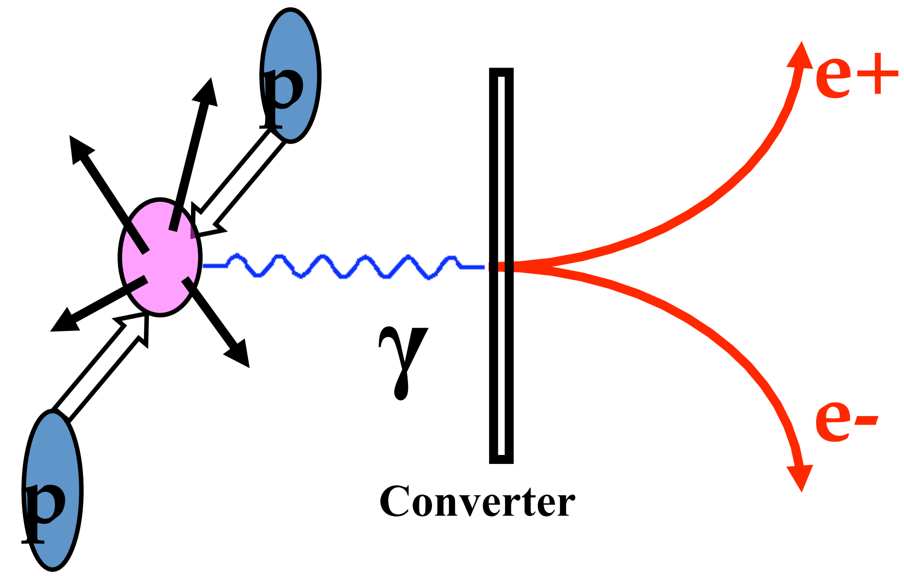


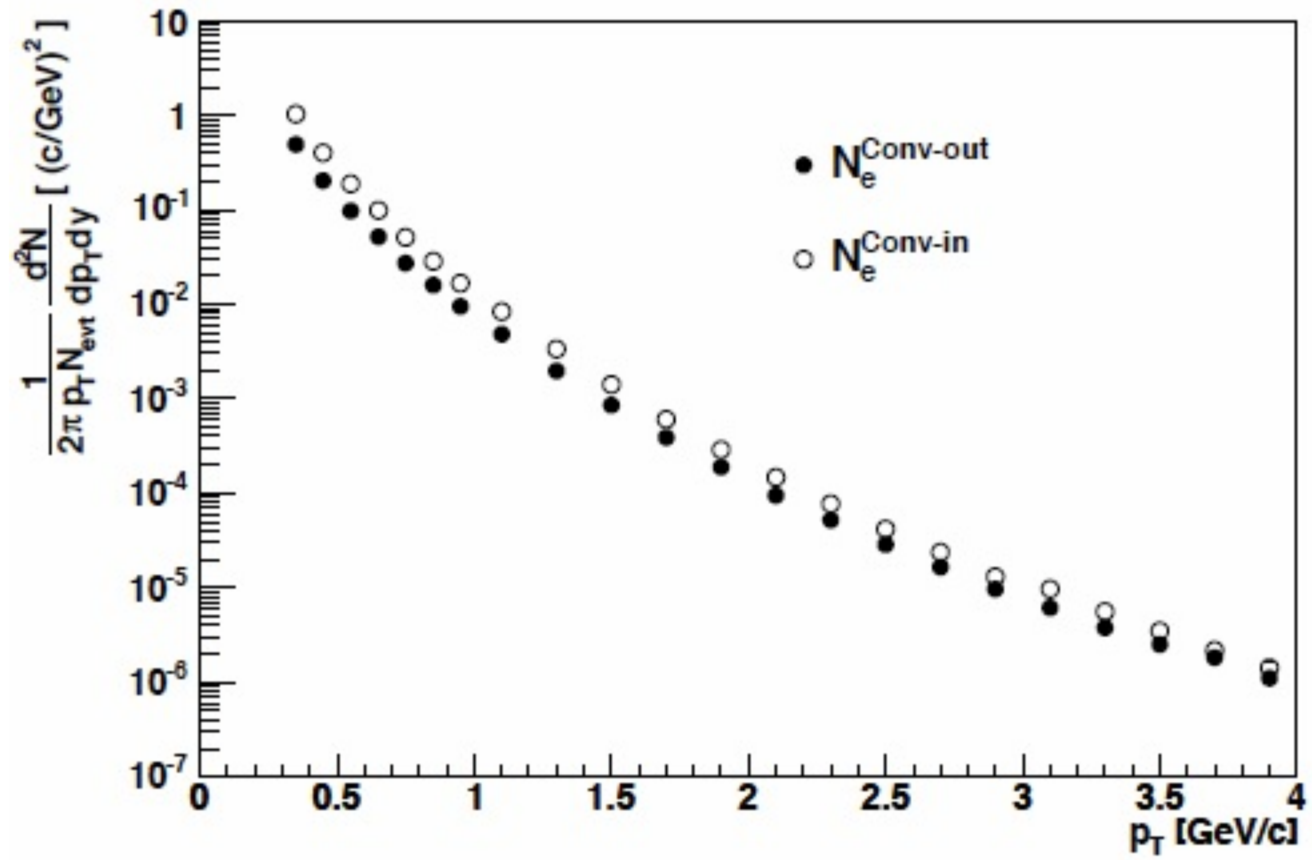
Converter method

- Converter material of known thickness (1.68 X_0) placed around beam pipe

- Increase of background by a fixed factor due to photon conversions

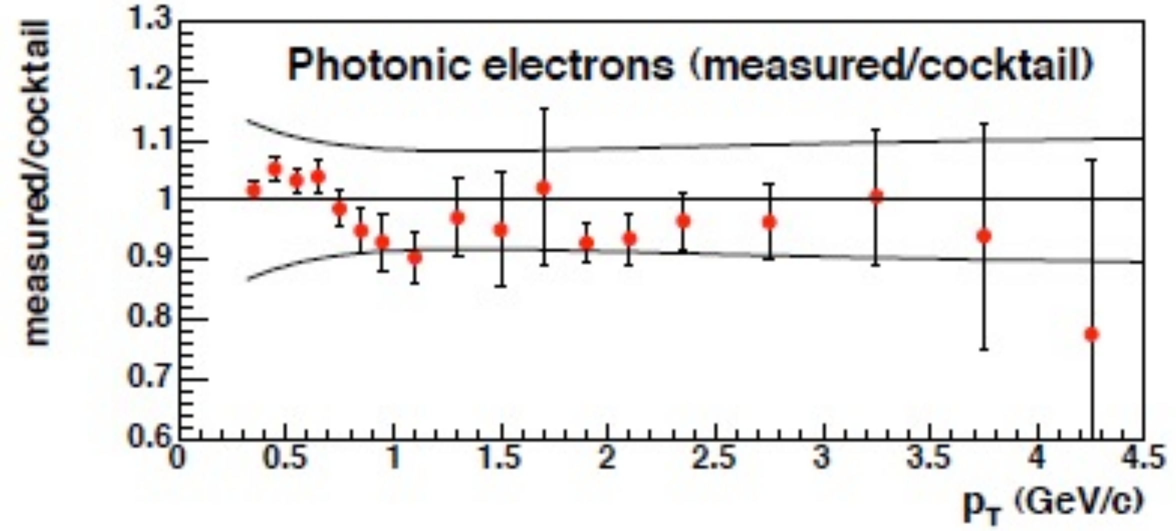
$$
\begin{aligned}
N_e^{\mathrm{Conv-out}} &= N_e^{\gamma} + N_e^{\mathrm{Non-}\gamma}, \\
N_e^{\mathrm{Conv-in}} &= R_{\gamma} N_e^{\gamma} + (1-\epsilon) N_e^{\mathrm{Non-}\gamma}
\end{aligned}
$$

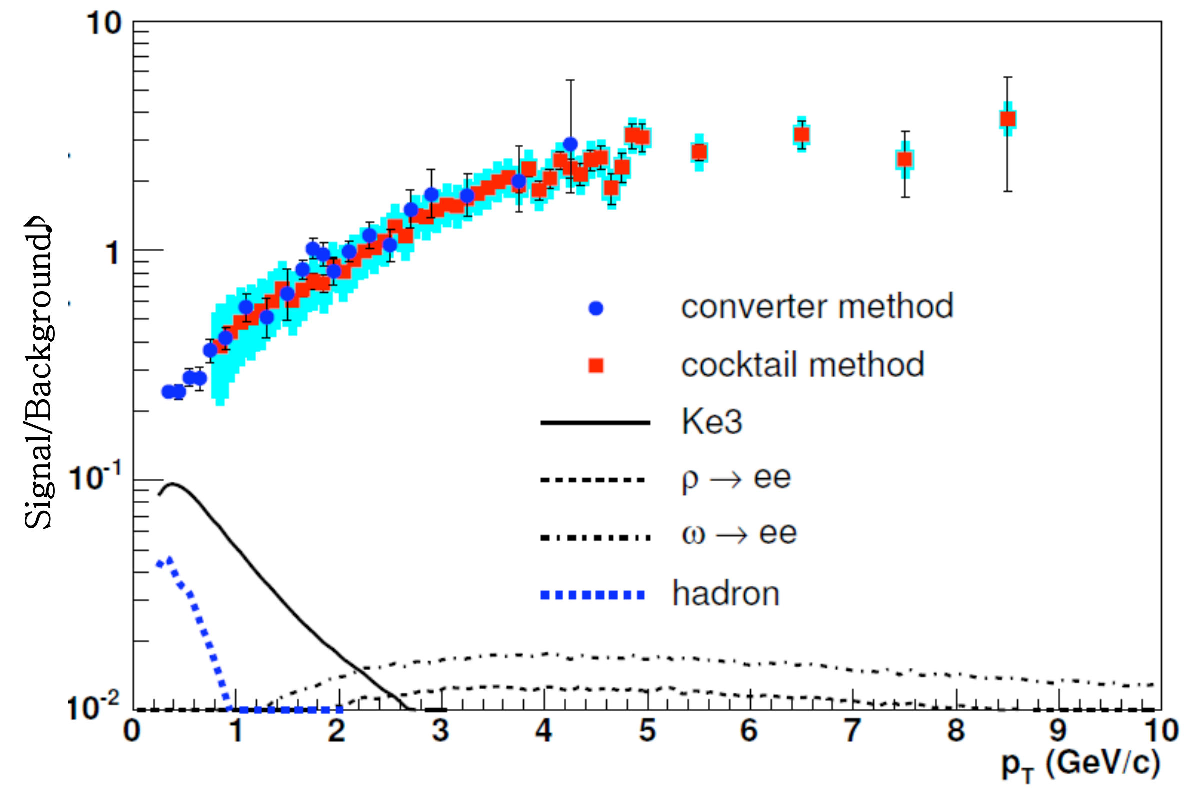




Cocktail vs. Converter Method

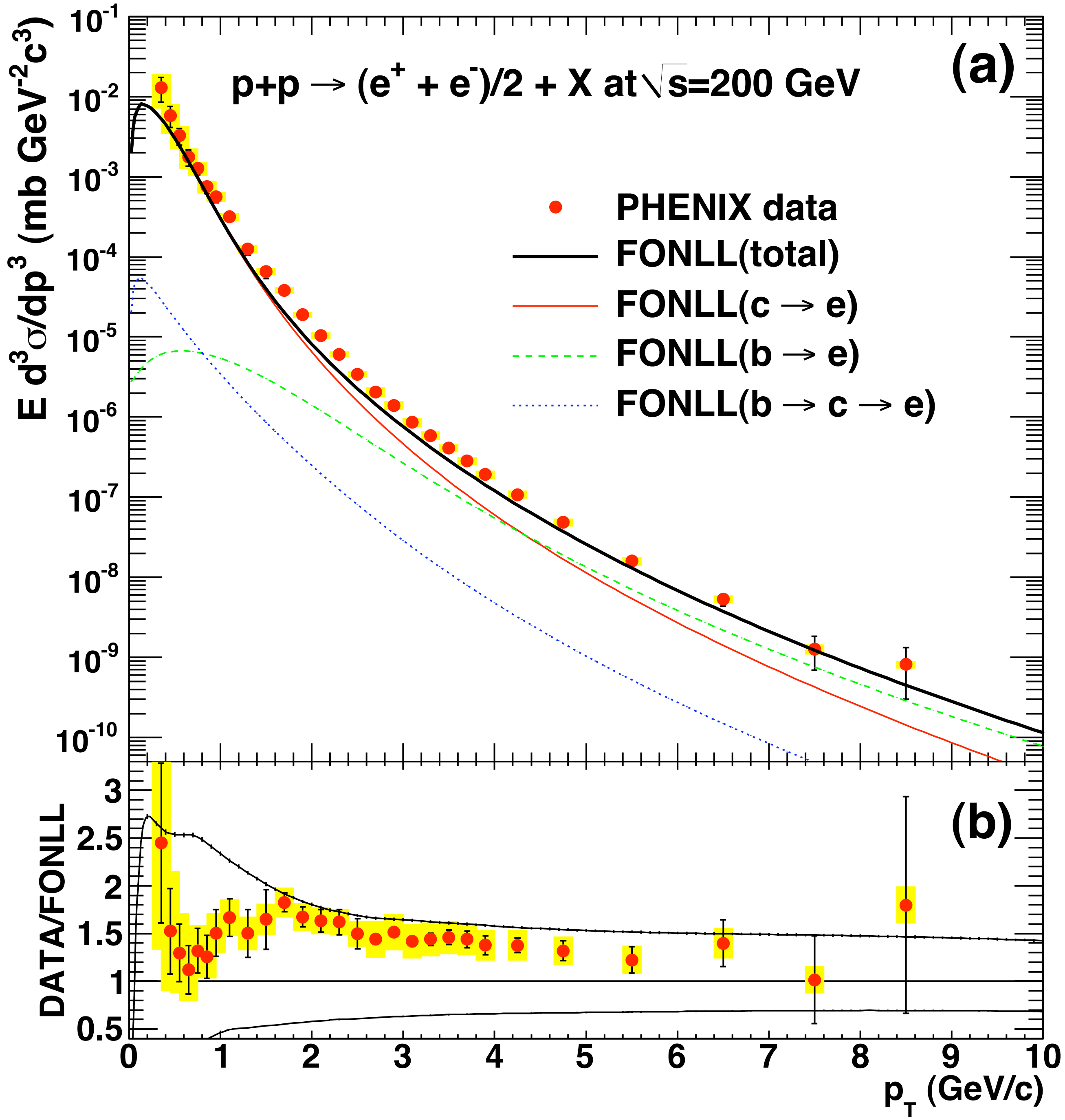
- Good S/B > 1 for above 2 GeV/c
- Good agreement between two methods
- Extensive P_T coverage
- Good S/B essential for v_2 analysis





Heavy flavor electron spectrum in p+p collisions @ 200 GeV

- Necessary baseline measurement for heavy ion collisions
- Latest cocktail (Including J/ψ contribution at high p_T)
- Agreement with FONLL (c+b) prediction **PRL 95 122001(2005)**
- Good agreement in spectral shape
- σ_{cc}= 567 ± 57(stat) ± 224(sys) mb
- For bottom cross section need to know bottom to charm production ratio within HF electron spectrum

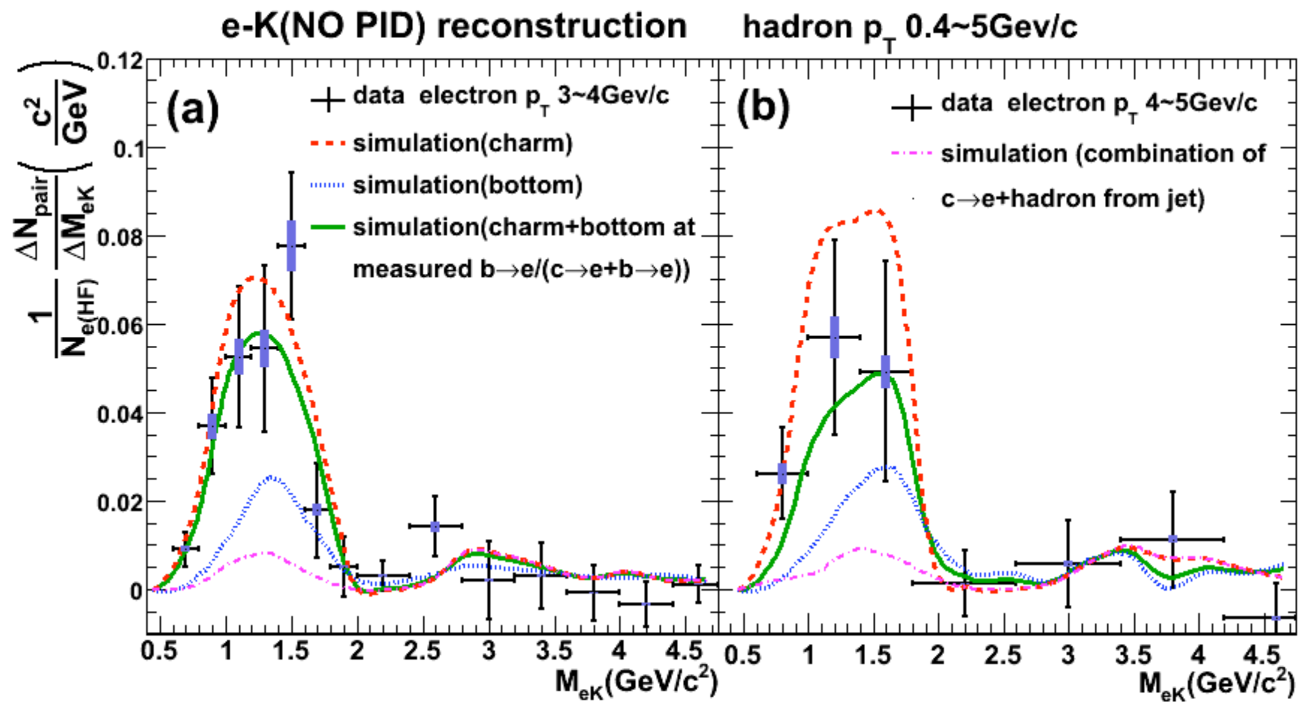


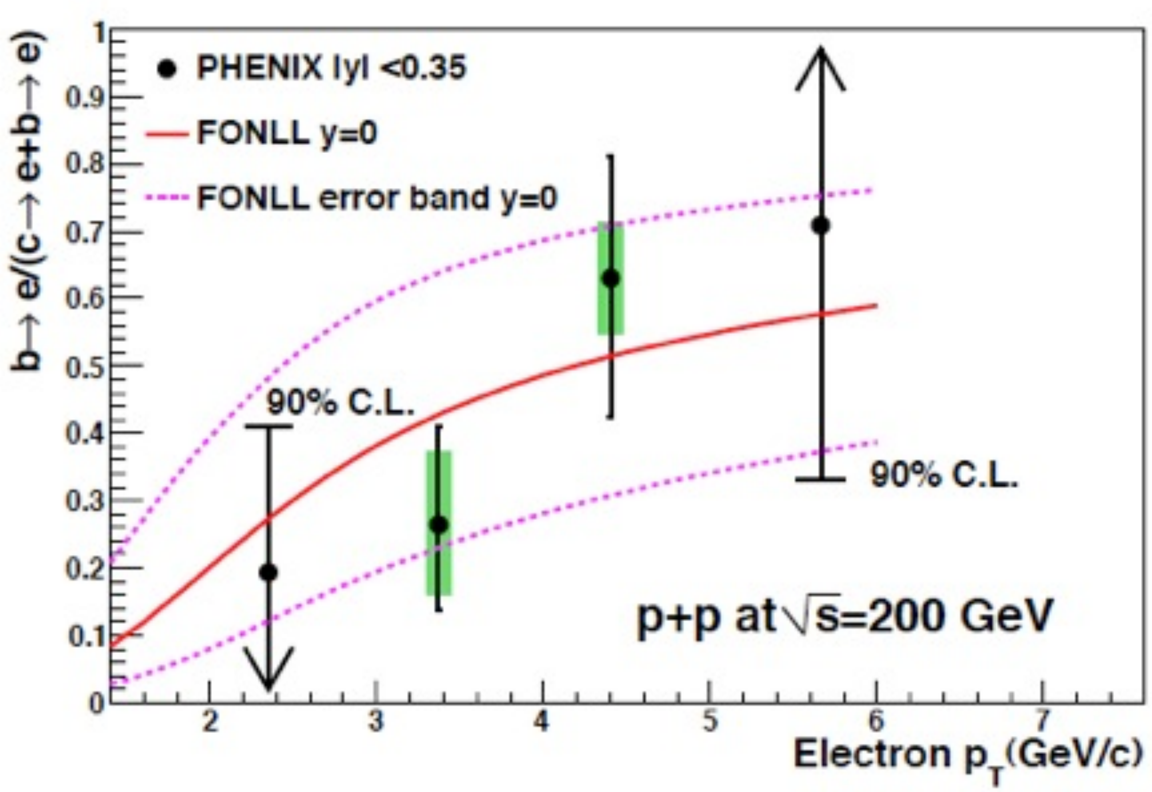
arXiv:1005.1627 (PHENIX)

Bottom to charm ratio (e-K correlations)

Reconstructing e-K(unidentified) invariant mass

Fit with PYTHIA simulation with varying b/c+b ratio





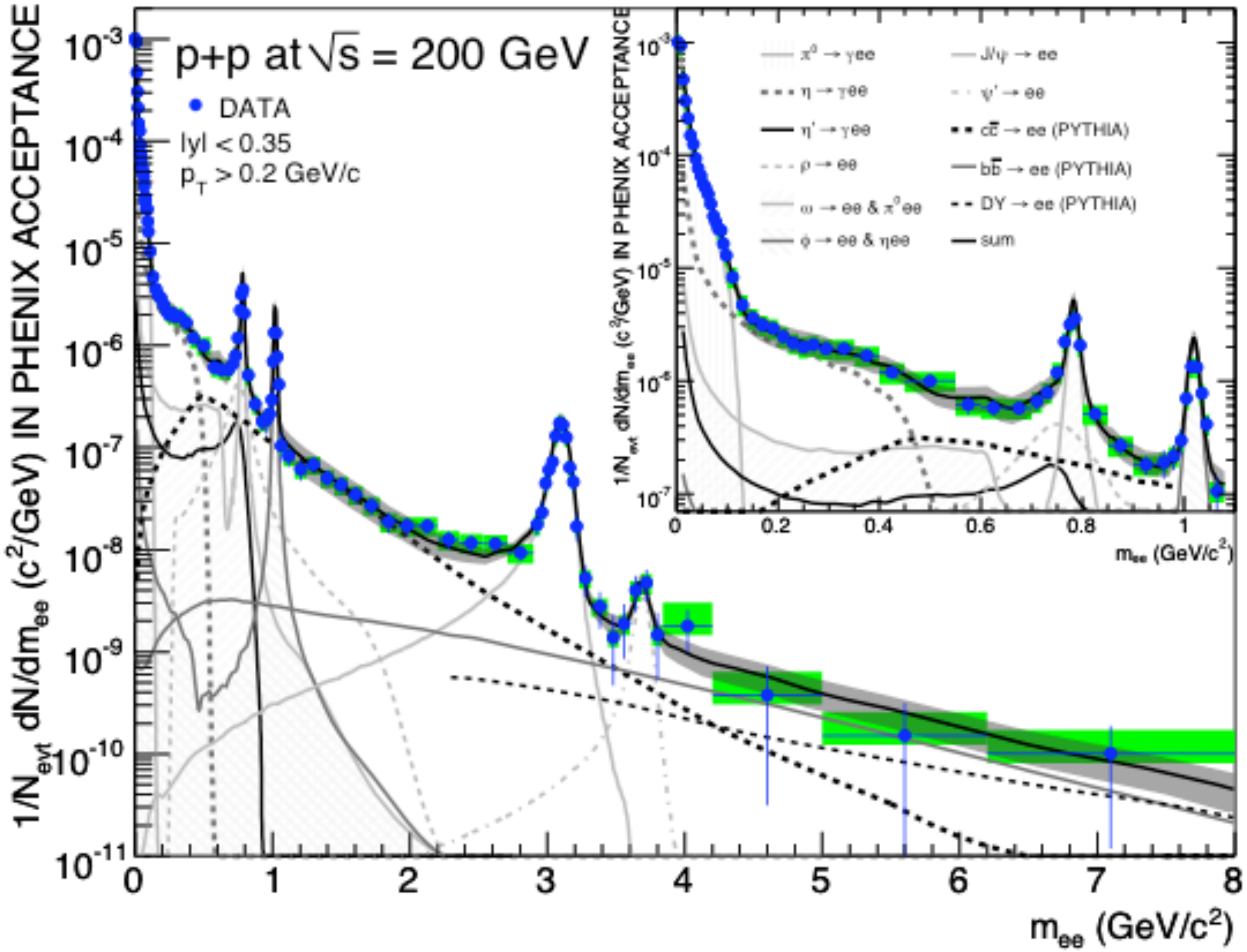
Bottom becomes dominant above P_T of 4GeV/c

Bottom quark cross-section:

$$\sigma_{bb} = 4.61 \pm 1.31(stat)^{+2.57}_{-2.22}(sys)\mu b$$

PRL 103 (2009) 082002

Open heavy flavor from di-electron continuum

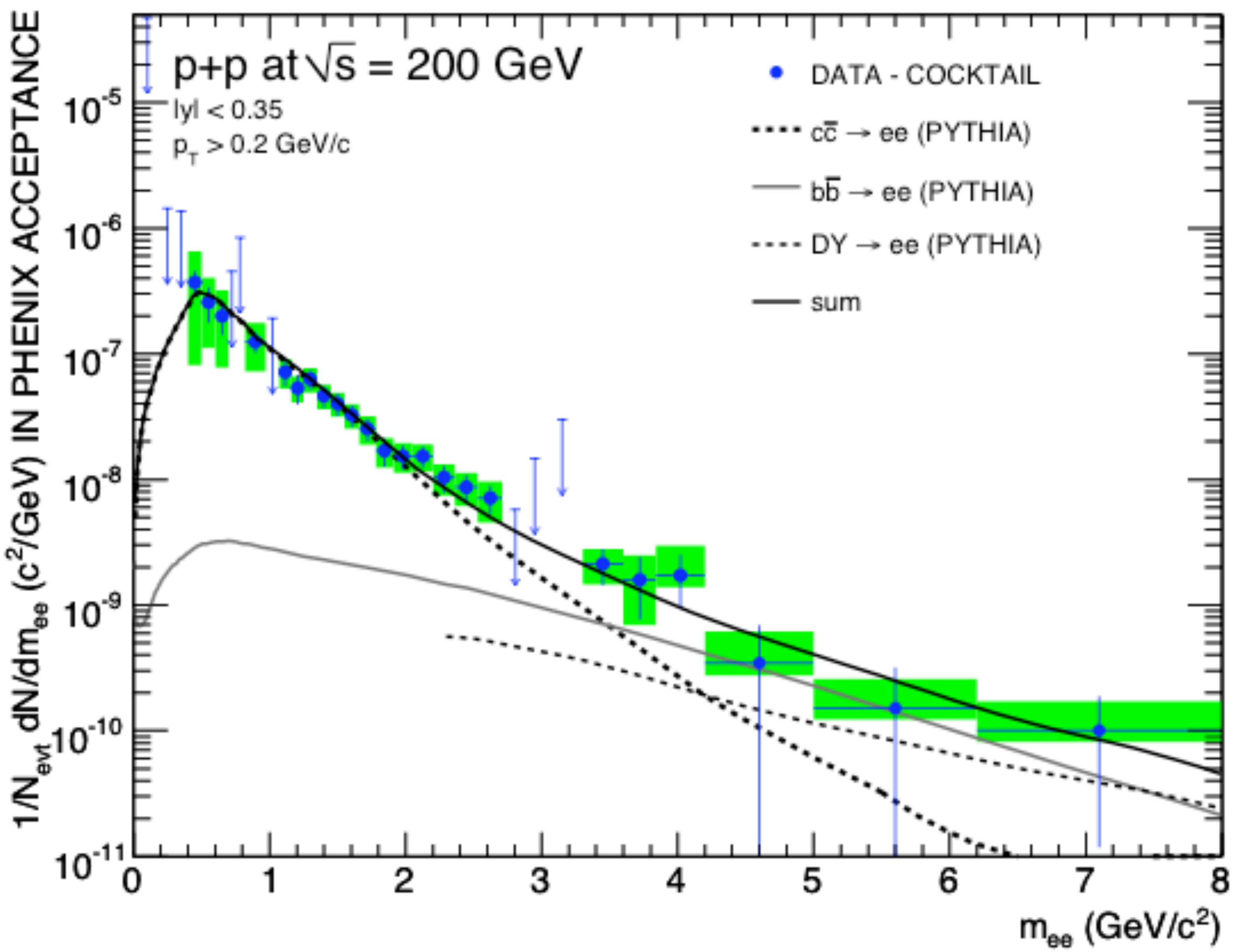


arXiv:0802.0050 (PHENIX)
Published

measured correlated e^-e^+ pairs

Independent cross-check for calculation charm and bottom quark cross sections:

Open heavy flavor from di-electron continuum



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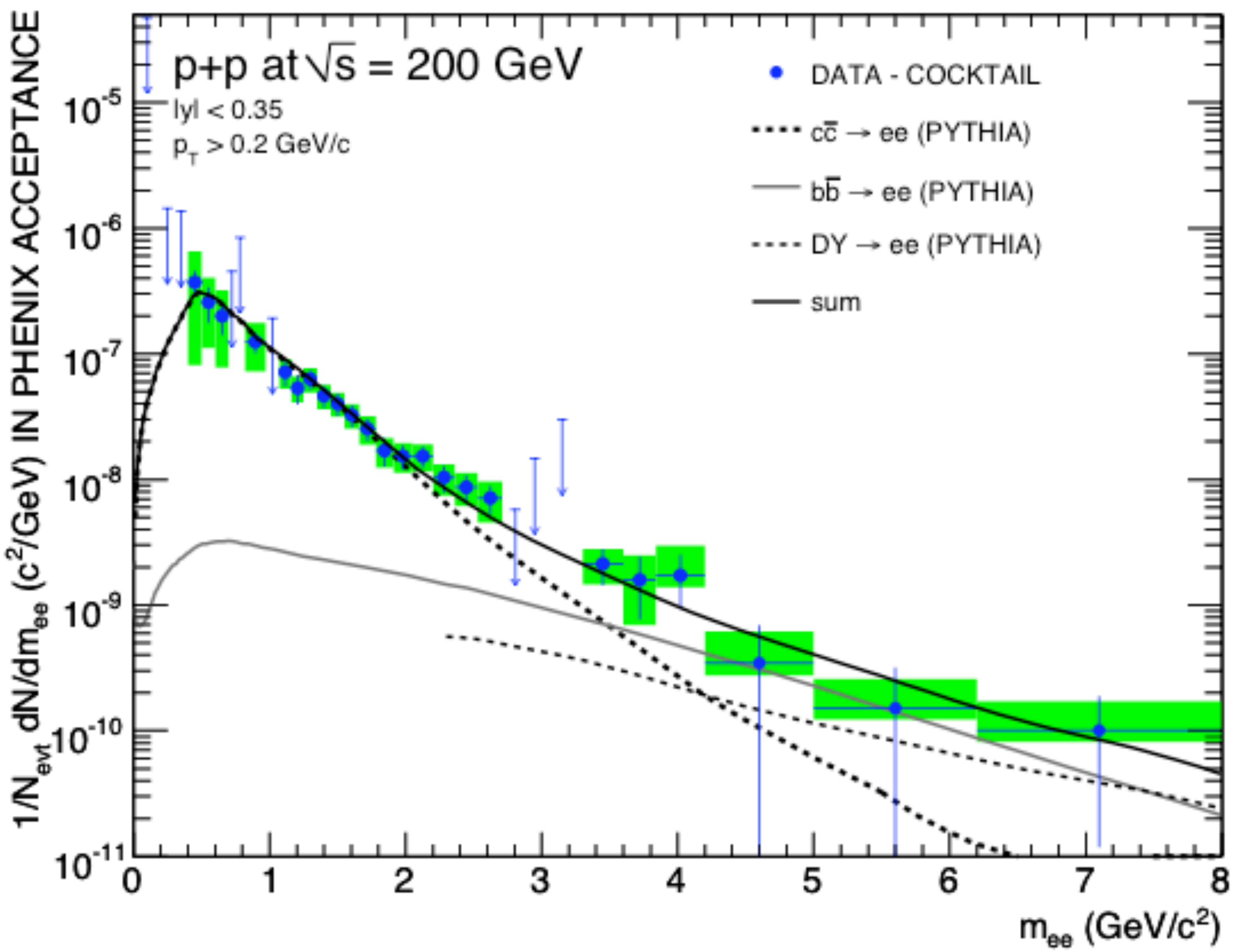
Open heavy flavor from di-electron continuum



arXiv:0802.0050 (PHENIX)
Published

measured correlated e^-e^+ pairs

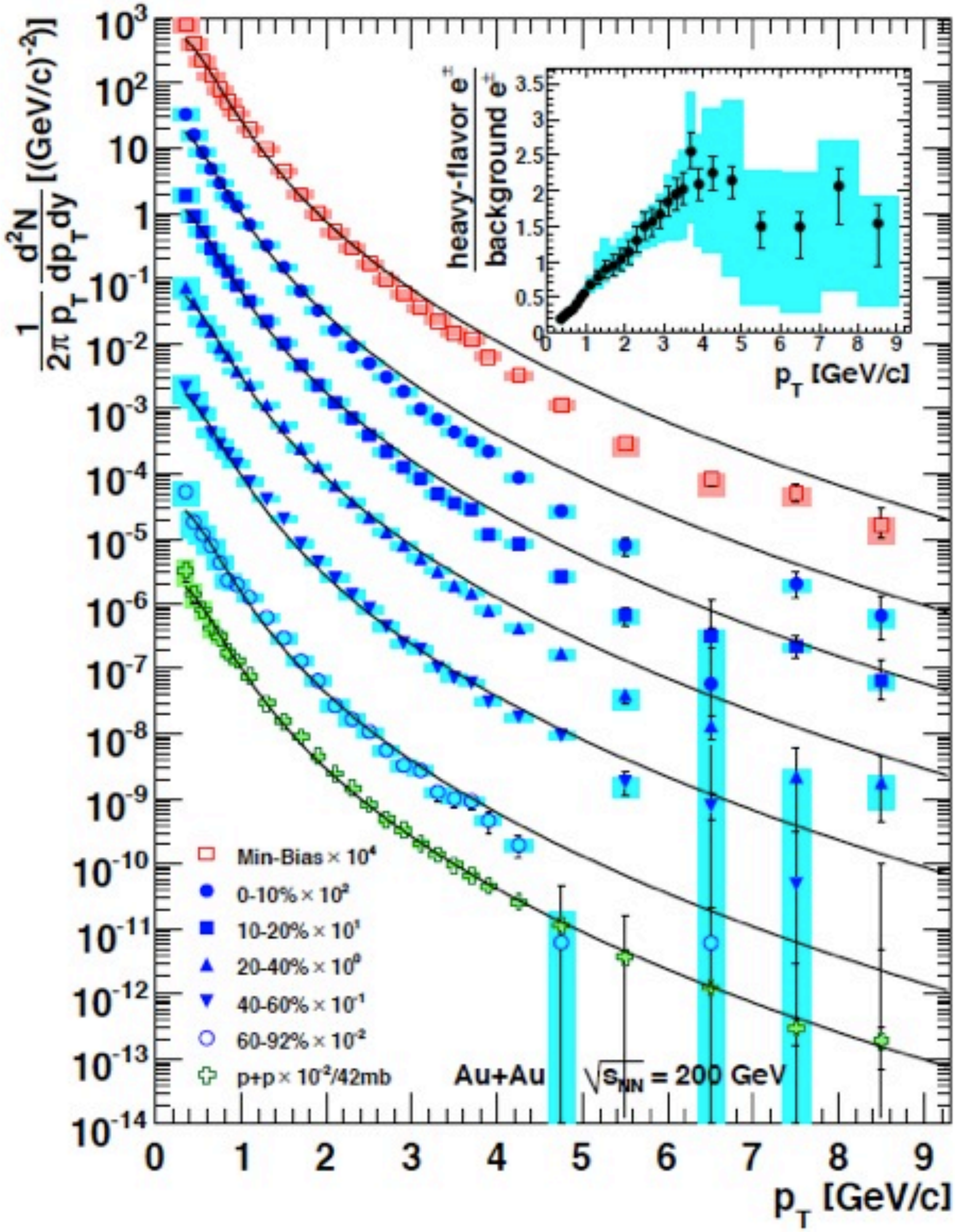
Independent cross-check for calculation charm and bottom quark cross sections:

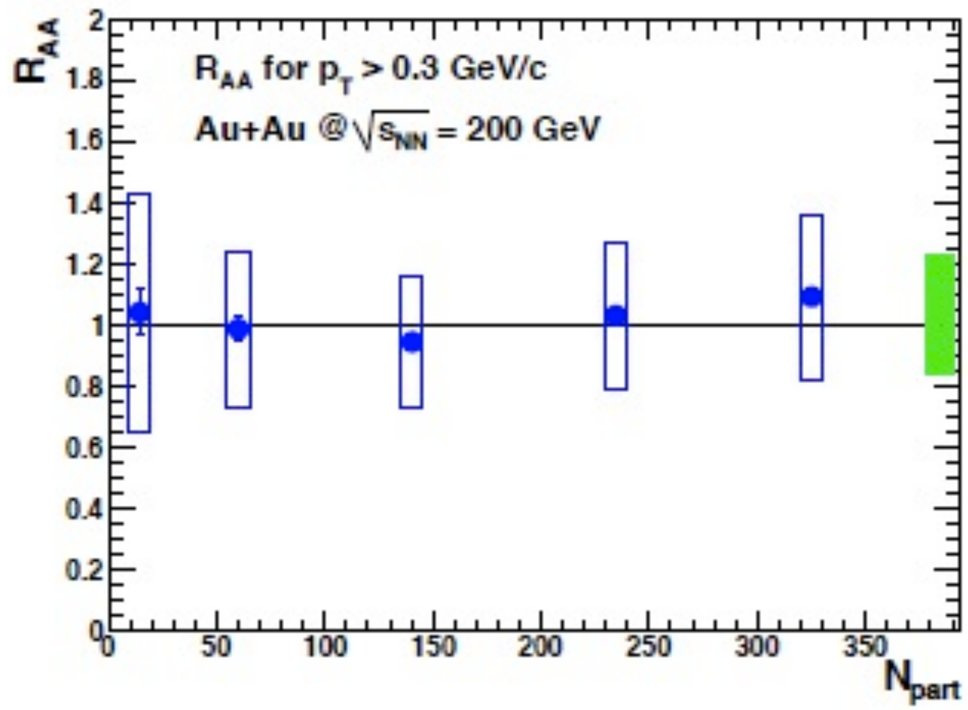
σ_{cc}= 544 ± 39(stat) ± 142(sys) ± 200(model) mb

σ_{bb}= 3.9 ± 2.5(stat) ± $^{3}_{2}$ (sys)

Good agreement with single heavy flavor electron results.

Heavy flavor e± spectra in Au+Au @ 200 GeV



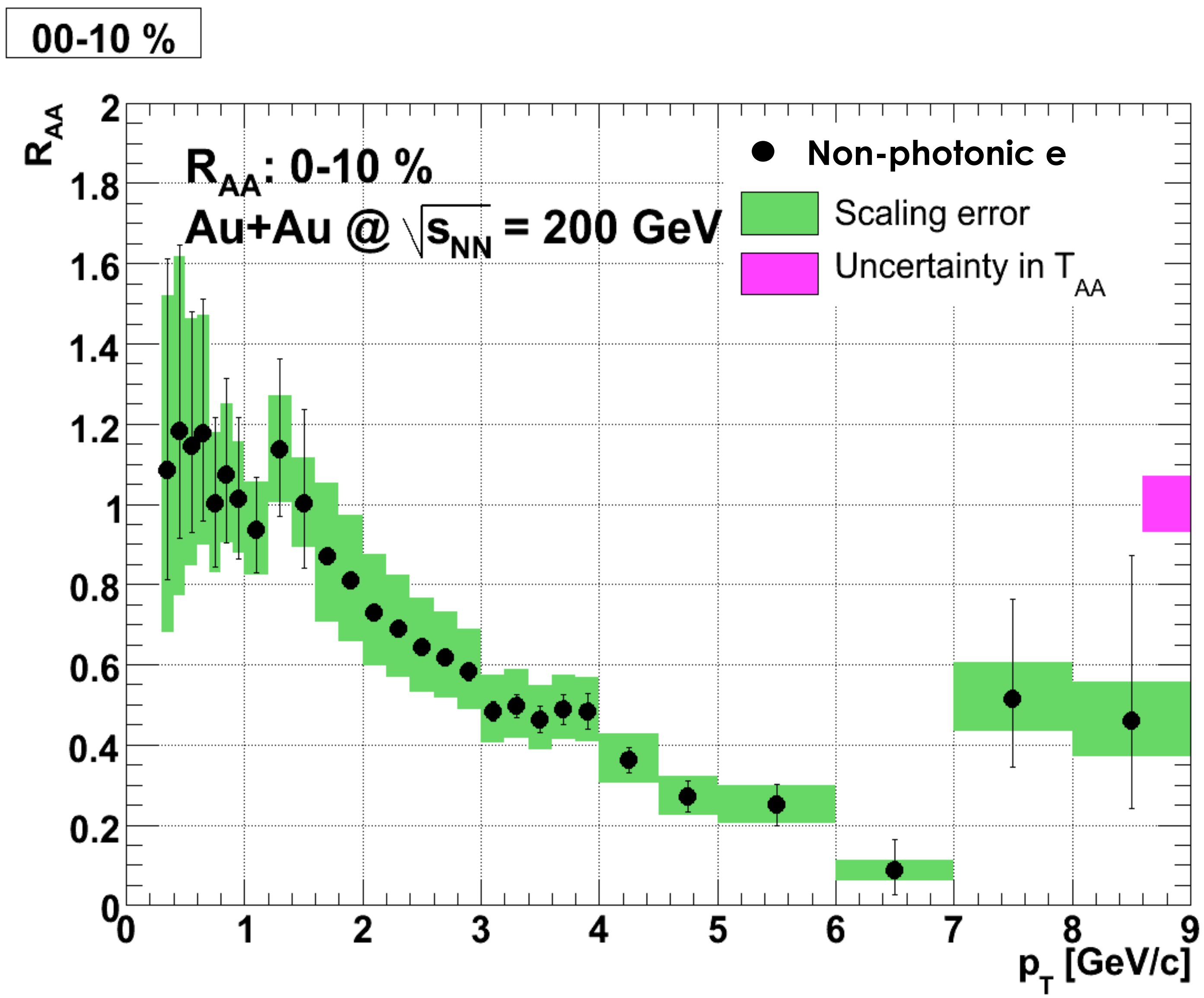


Total cross section scales with N_{part}

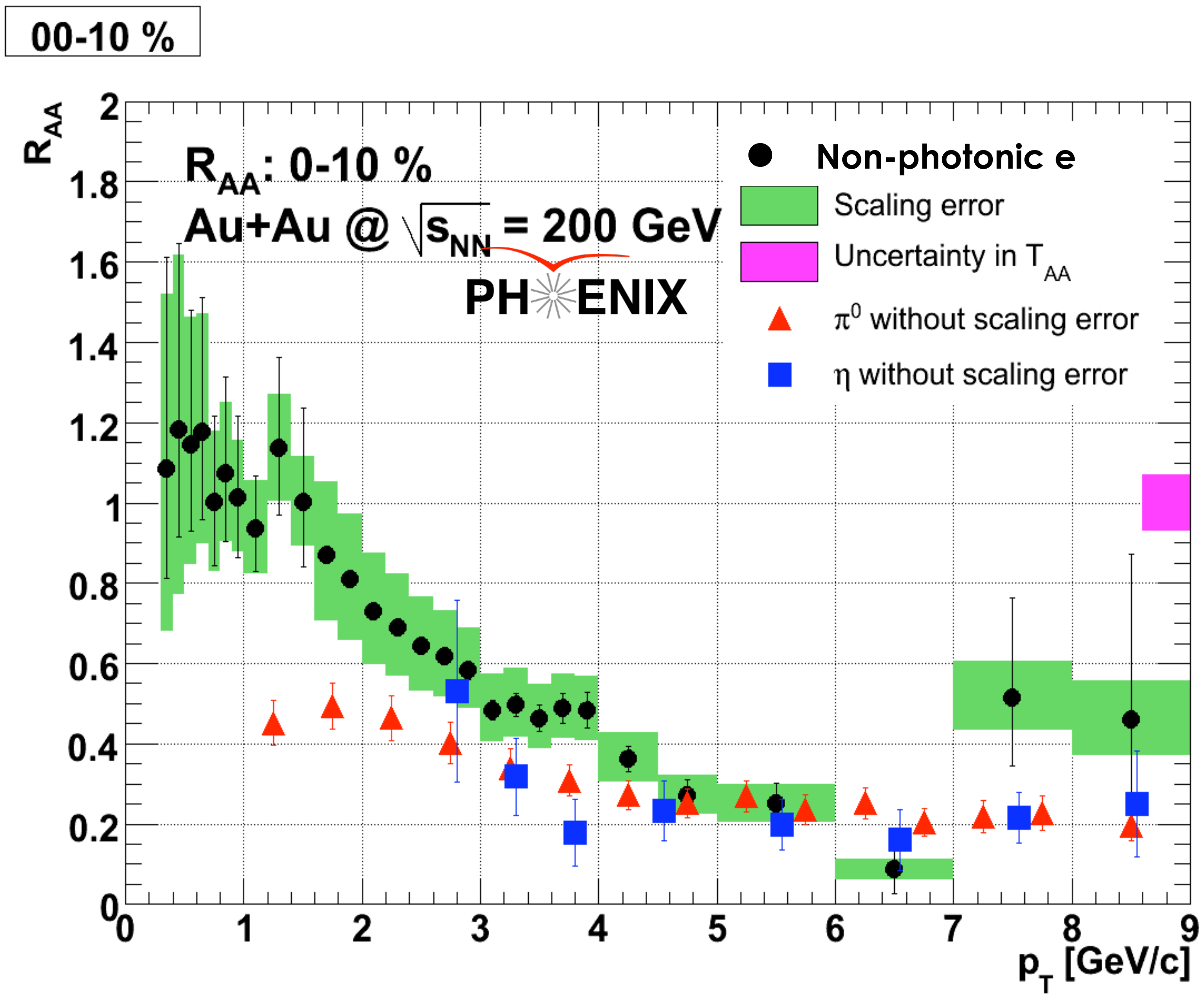
Visible large suppression in more central data selections at $p_T > 3$ GeV/c

arXiv:1005.1627 (PHENIX)

Nuclear modification factor vs. p_T



Nuclear modification factor vs. p_T



Suppression at $p_T > 3$ GeV is almost as much as for π_0 and ϱ

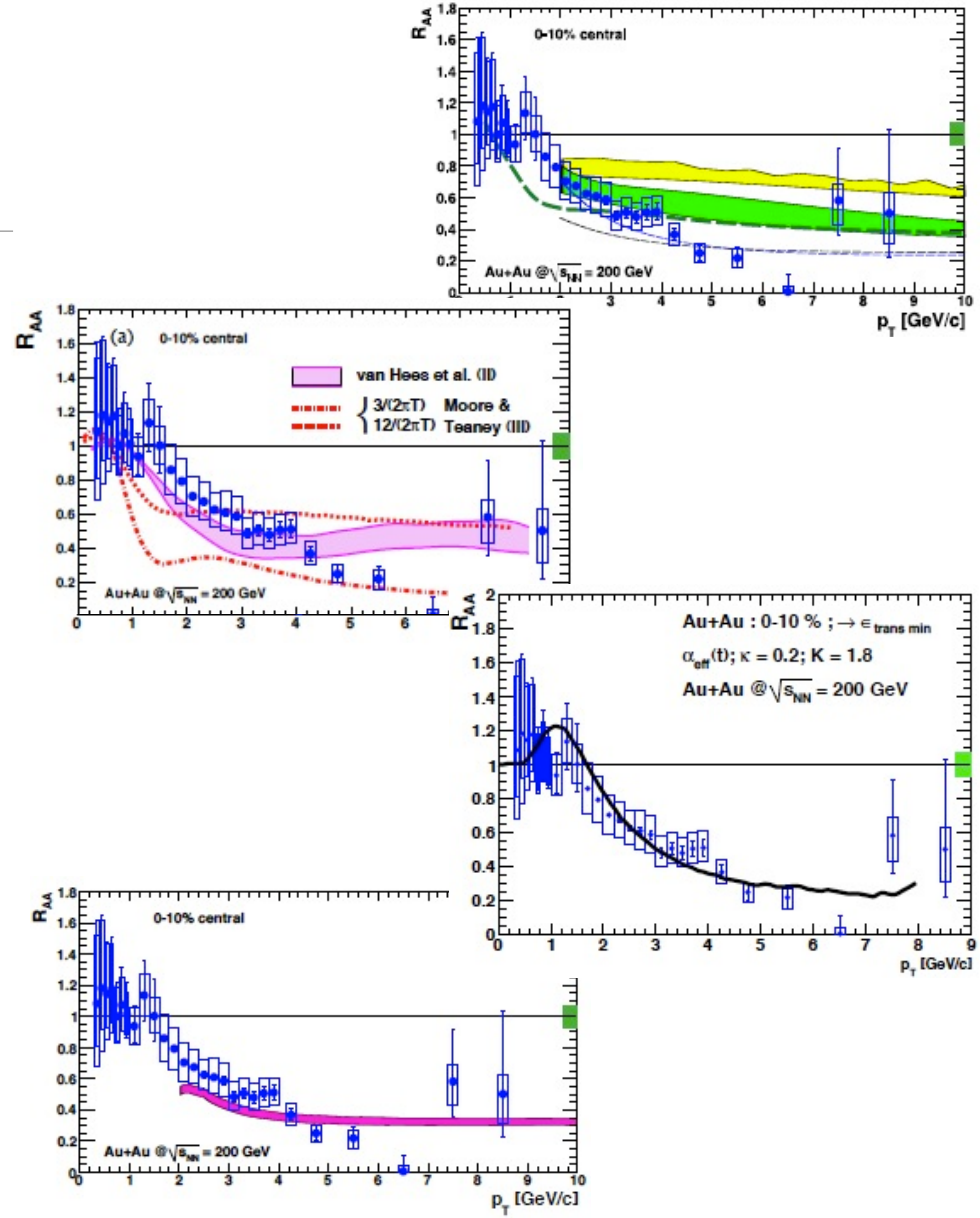
But shouldn't heavy quark radiate less gluons then light quarks (dead cone effect) based on pQCD ?

Perhaps asking too much from pQCD when medium is so strongly interacting

What about other mechanisms of energy loss?

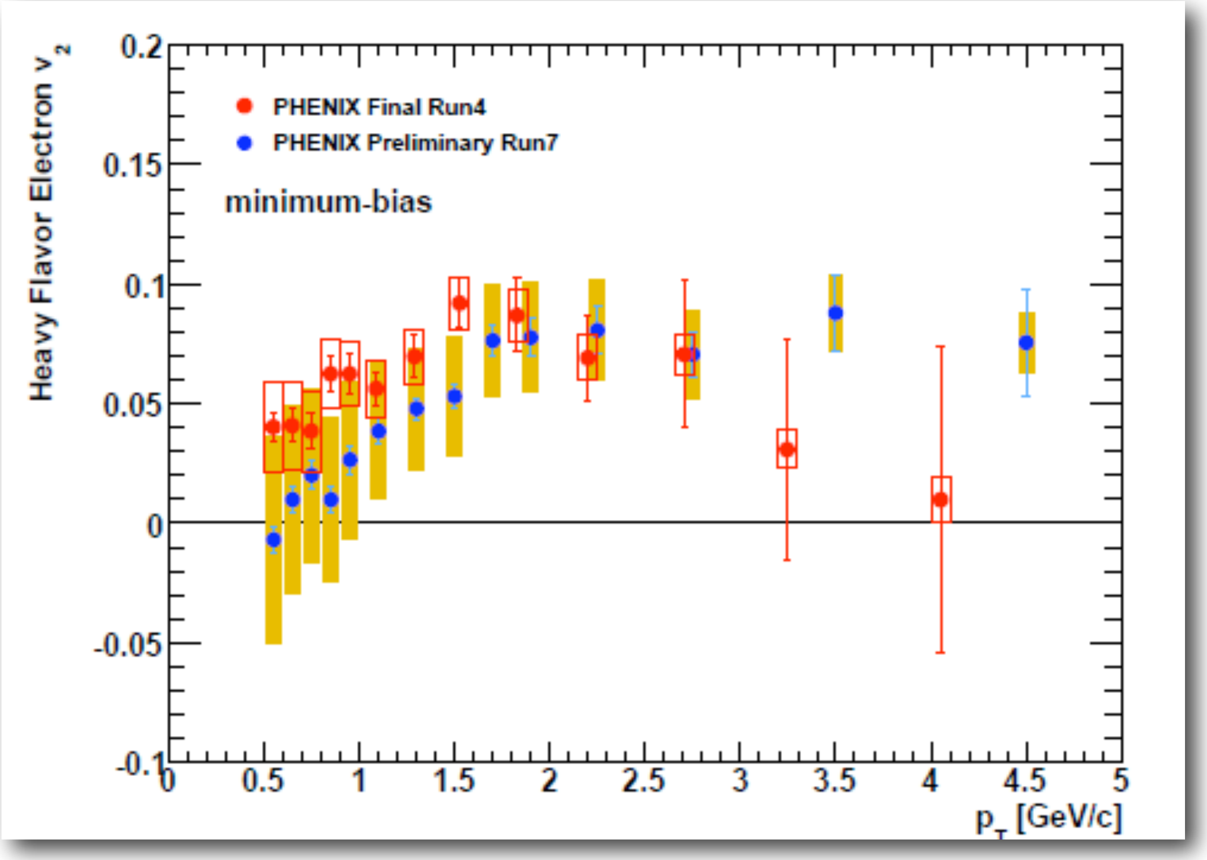
Nuclear modification - theory(ies)

- Energy loss due to elastic scattering
- Heavy quark diffusion
- Heavy flavor meson dissociation
- Precise bottom to charm ratio critical
- Simultaneous matching to both R_{AA} and v_2 needed



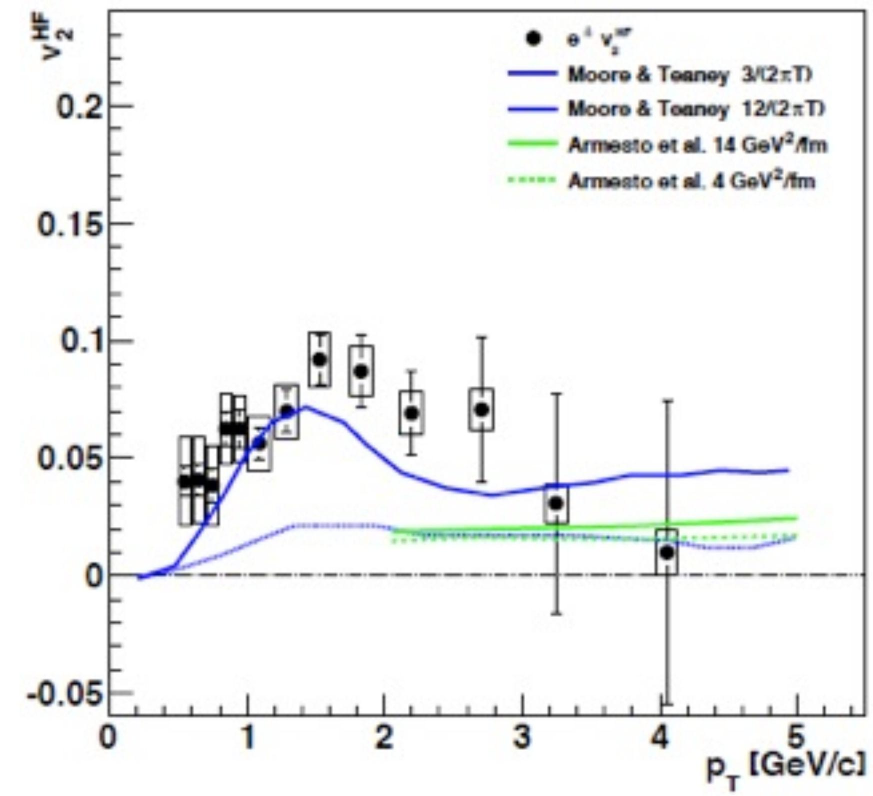
Elliptic flow - V_2

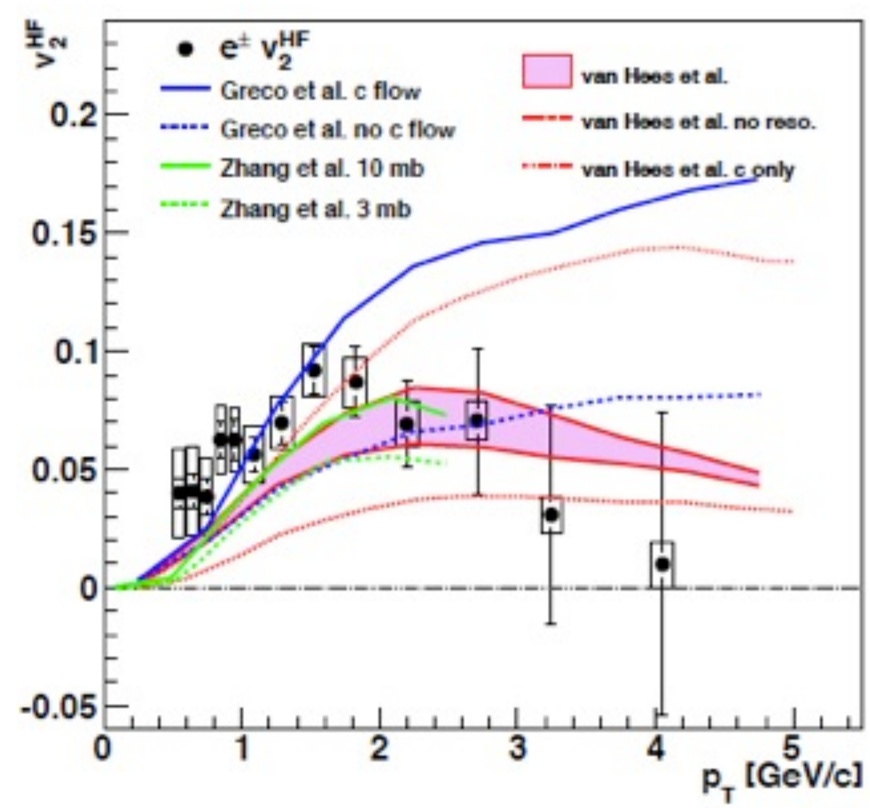
- Large HF electron v_2 from Run-4 Au+Au measurement data (First measurement)
- Extended and improved measurement at high p_T with Run-7 data due to improved reaction plane resolution (new reaction plane detector)
- v2 measurements in several centrality classes



So do HQs flow ?

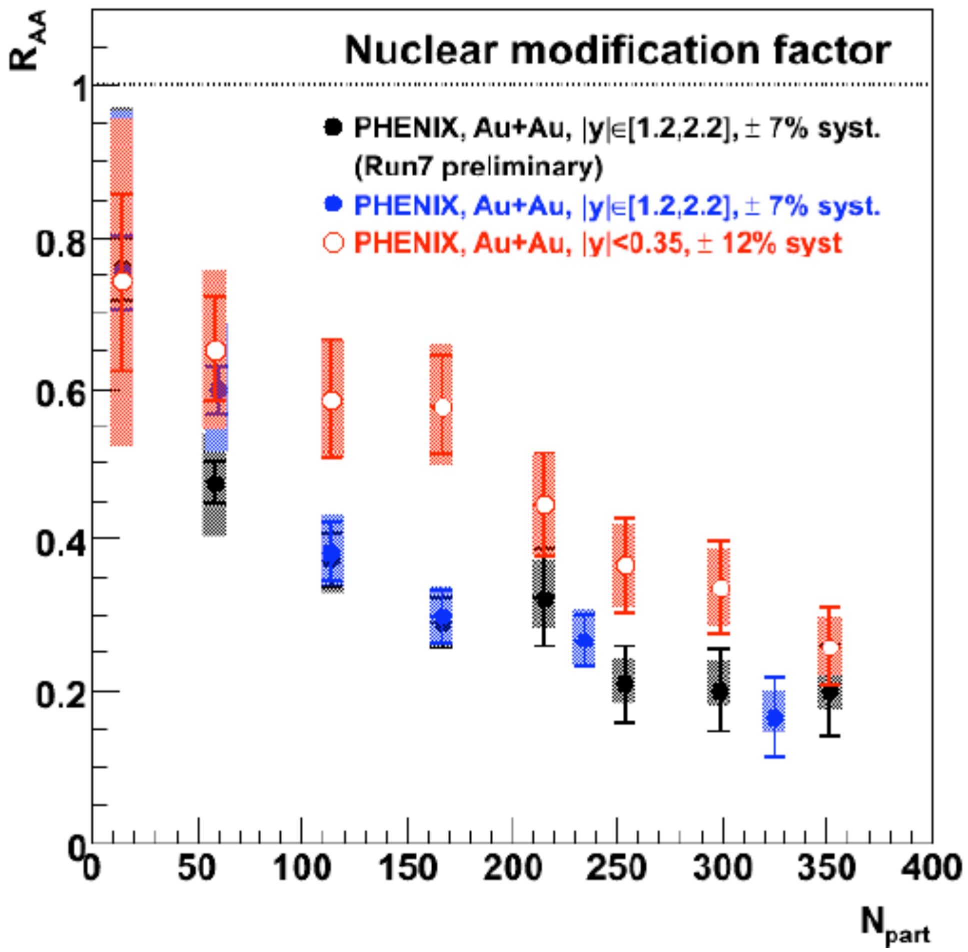
- Large HF electron v_2 doesn't automatically translate to large HQ v_2
- Radiative energy loss models give only lower limit on v_2. Data in better agreement with models assuming stronger coupling with the medium
- Recombination scenarios favor sizable c-quark v_2
- Once again precise bottom to charm ratio or direct B and D meson measurements needed for further testing of models





Forward rapidity

- Full picture understanding needed
- No theoretical predictions of open heavy flavor muon production in forward rapidity
- PHENIX J/ψ data indicates larger suppression in the forward rapidity
- Larger cold nuclear matter effects.
- please



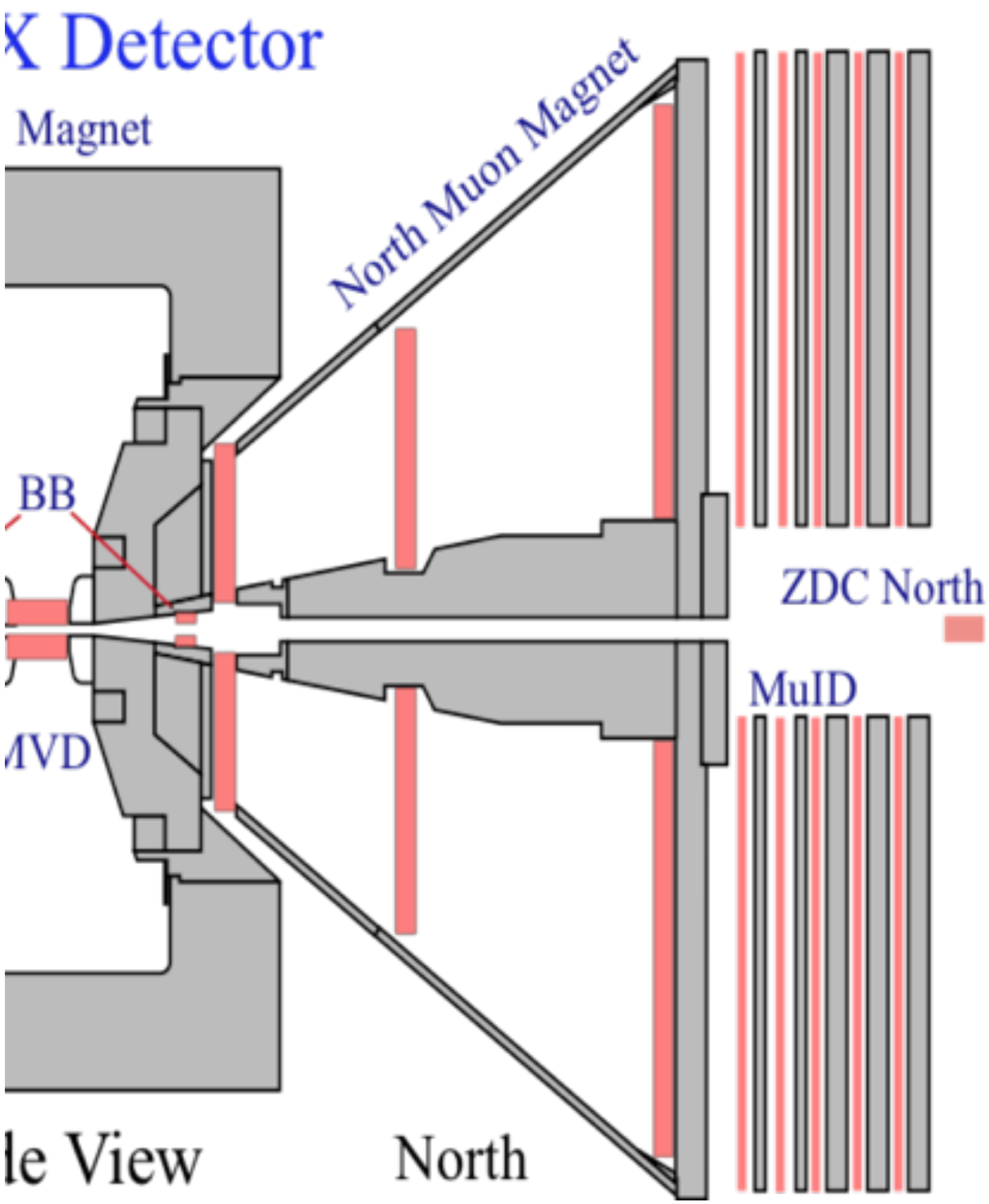
Measuring single muons in muon arms

SIGNAL:
"Prompt" muons – muons resulting from decays of heavy quarks

BACKGROUND:
Decay muons – muons from hadron decays

Punchthrough hadrons – hadrons punching through the entire detector

OTHER SOURCES
Stopped hadrons – hadrons stopping in the shallow gaps due to nuclear interaction with the absorber.



“Hadron cocktail”: estimating Background at forward rapidity

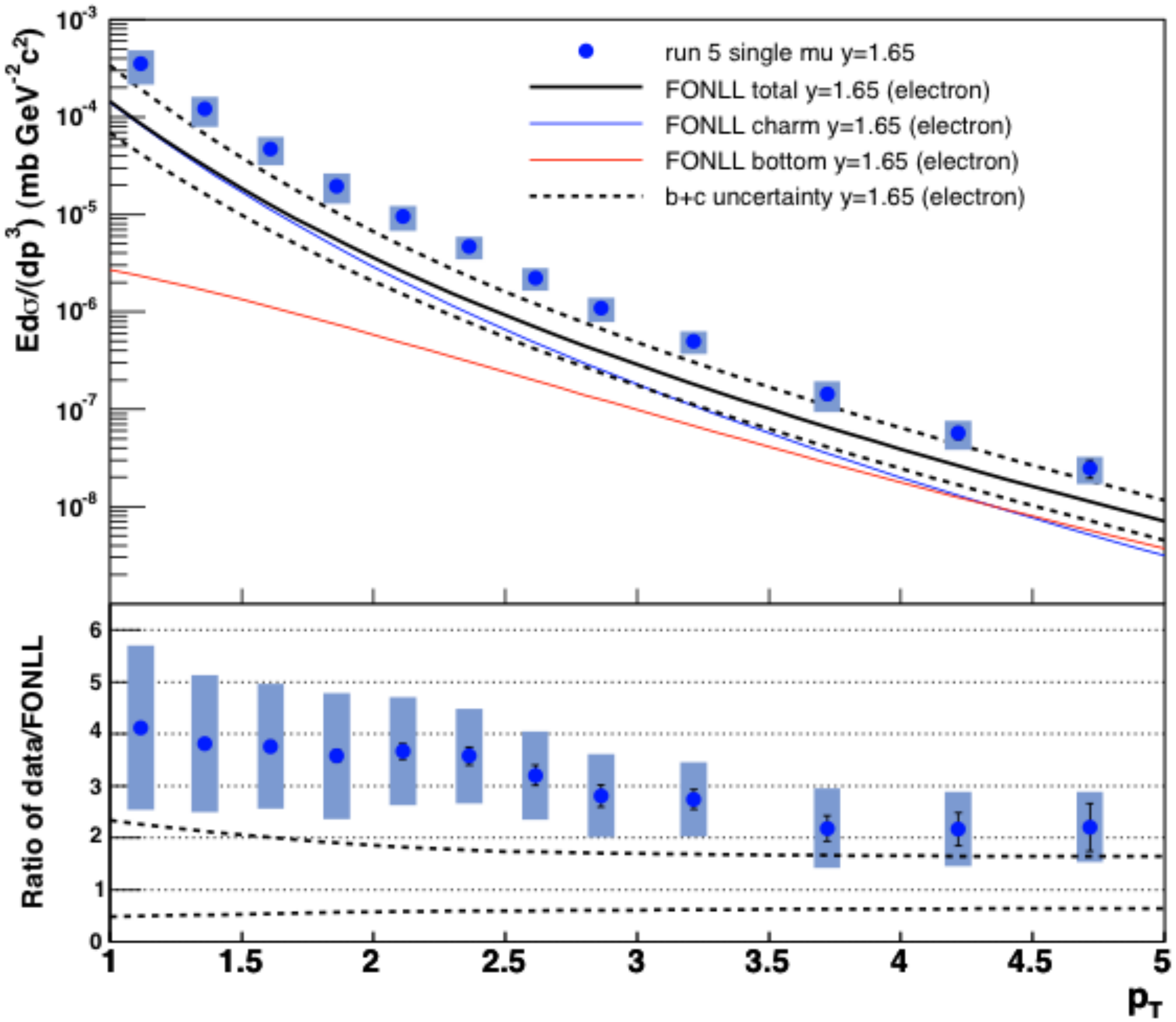
Cocktail is pre-constraint by matching with data

Generation of a “realistic” input P_T spectra and mixture of dominant background sources (π, K, p …).

Particle propagation through PHENIX geometry using GEANT.

In heavy ion collisions “Embedding” simulated tracks into real events to reproduce effects of detector environment during heavy ion collisions .

Single muon spectra in p+p collisions (Run-5)



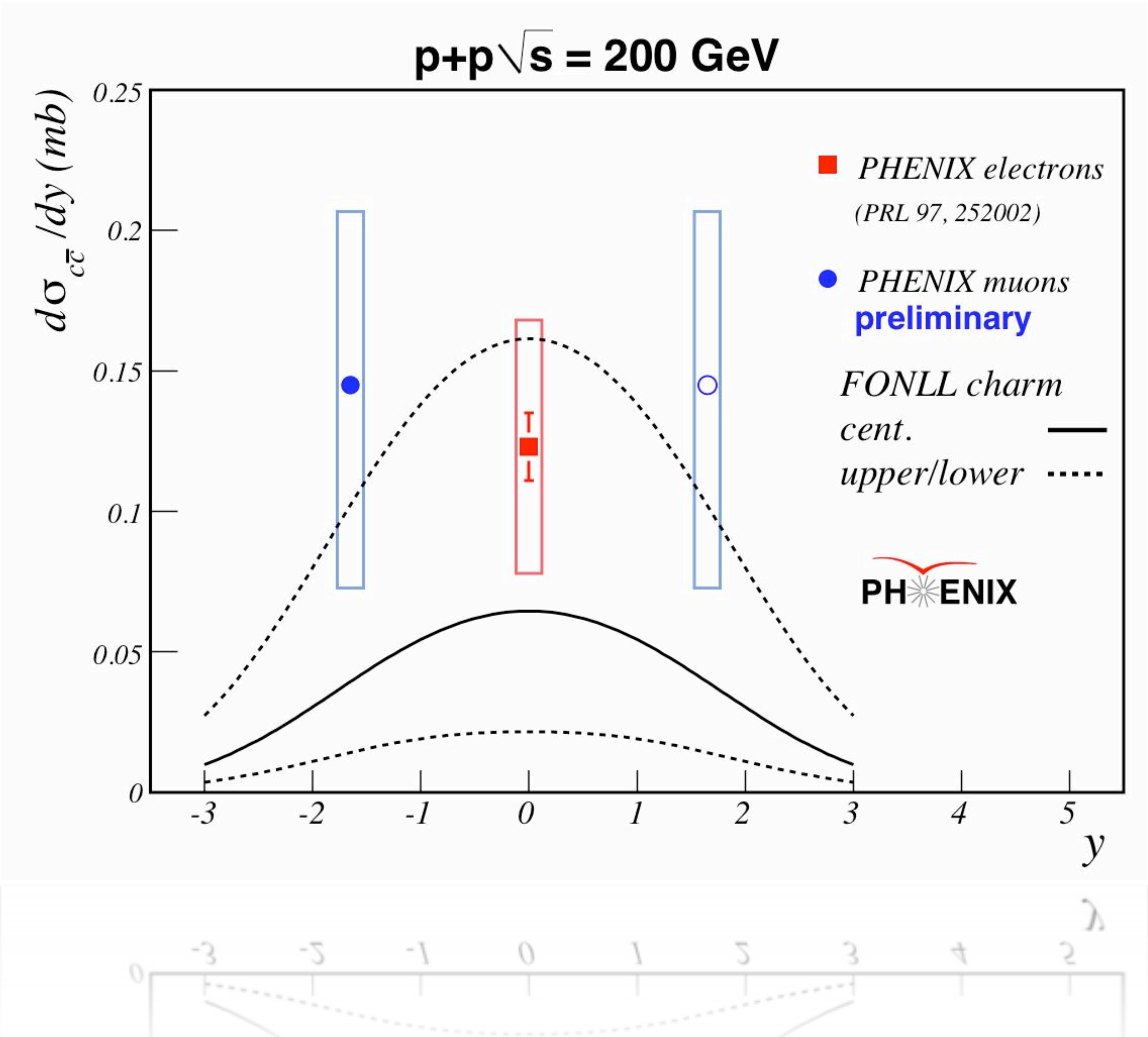
Independent South/North arms cross-check

Agreement with previous single muon result (Run-2)

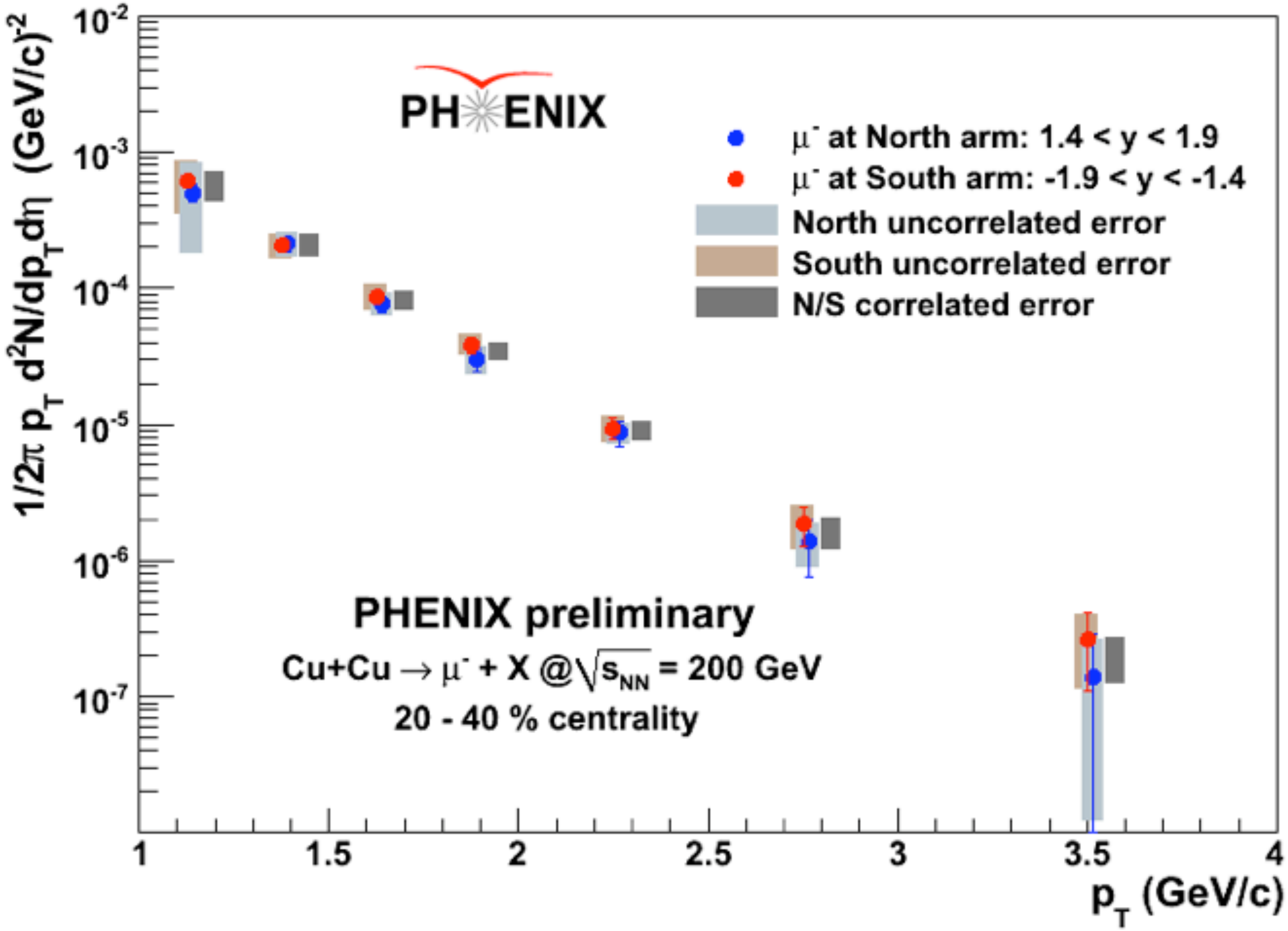
Large systematic uncertainties in low p_T region

Better agreement at high pT with FONLL(c+b) prediction at y = 1.65

Cross section vs. y



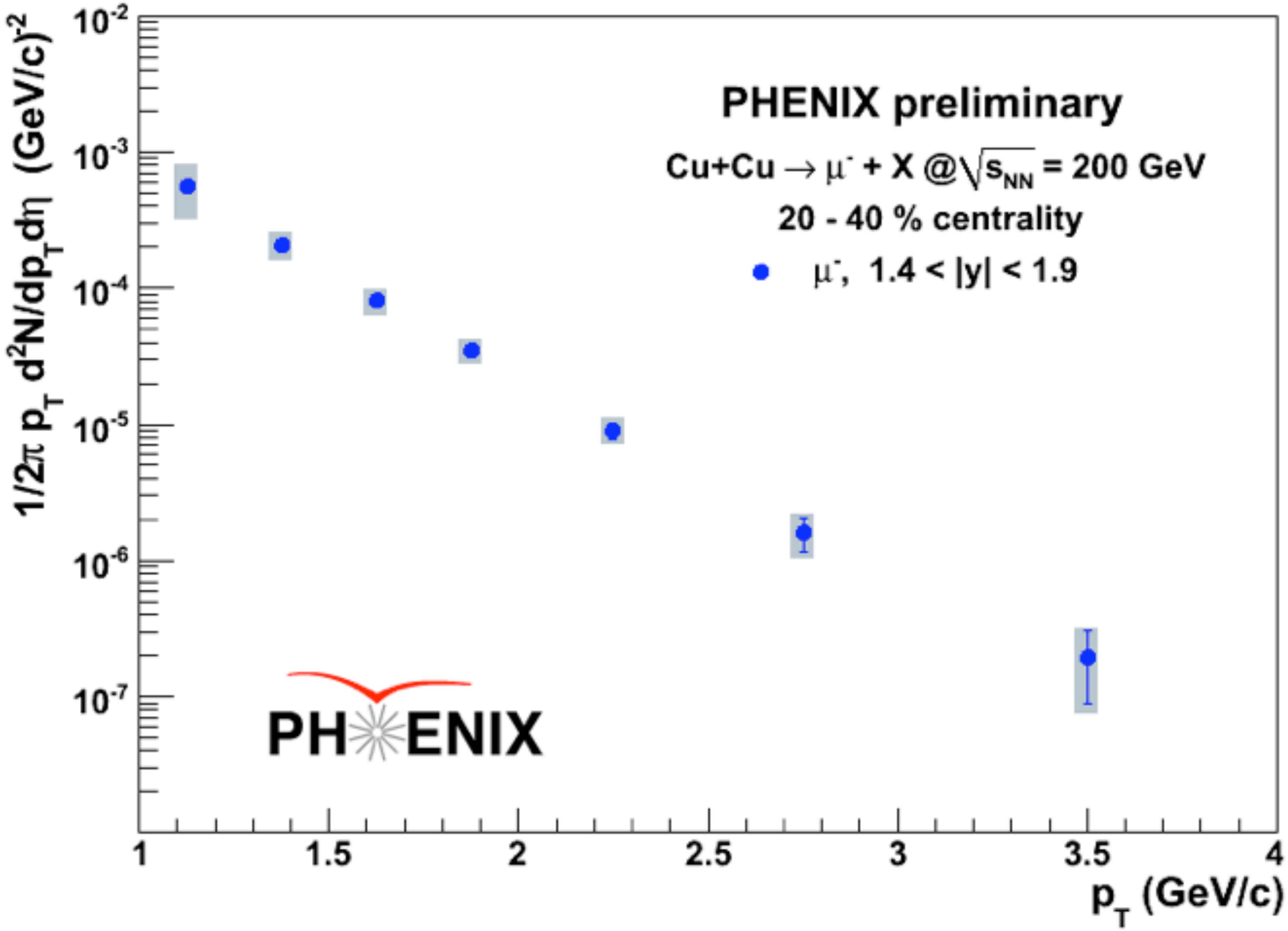
Single muon spectra (Cu+Cu)



Good agreement between single muon spectra in the north and south arms

Reduced systematic after combining spectra

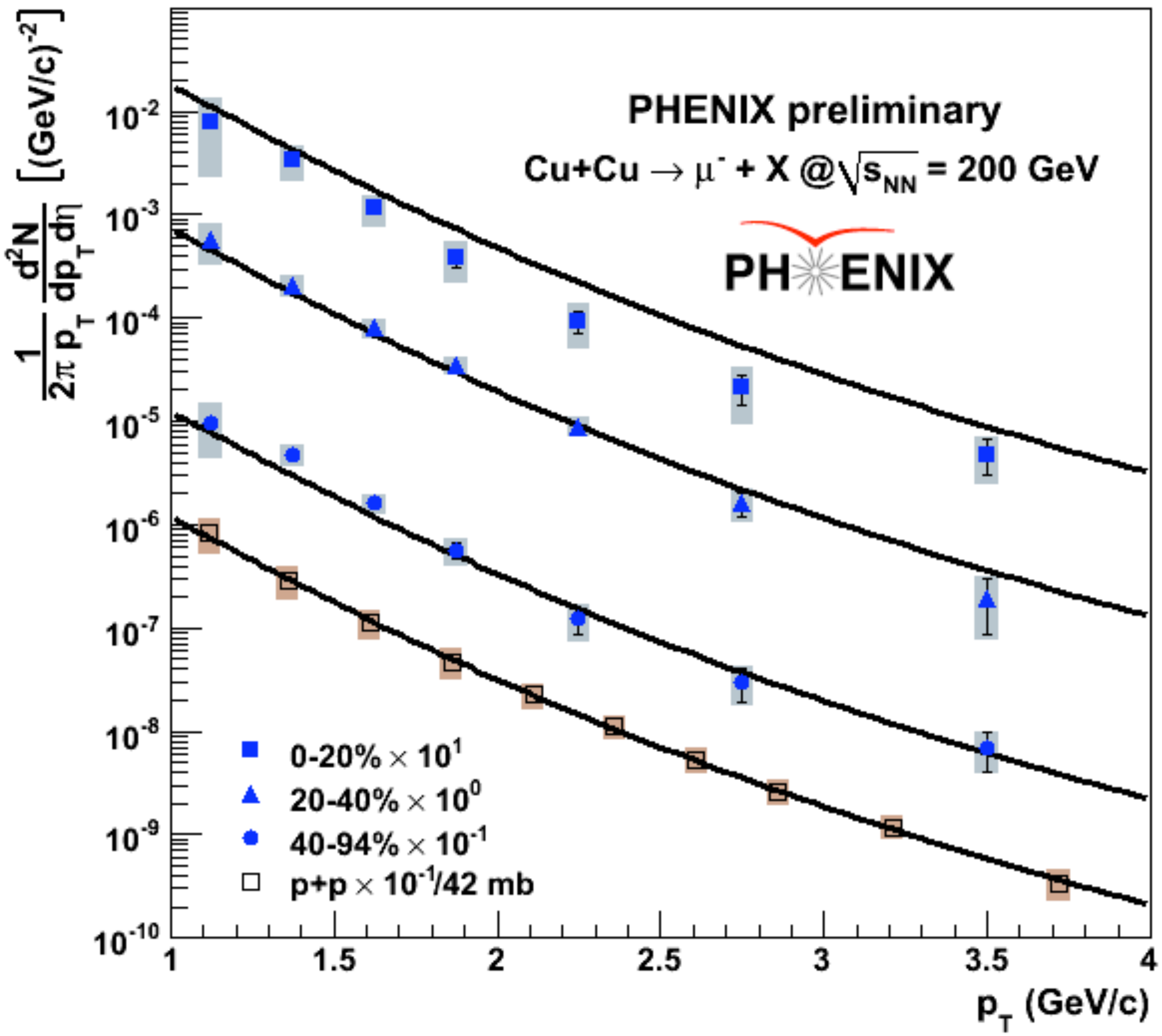
Single muon spectra (Cu+Cu)



Good agreement between single muon spectra in the north and south arms

Reduced systematic after combining spectra

Single muon spectra in Cu+Cu collisions @ 200 GeV

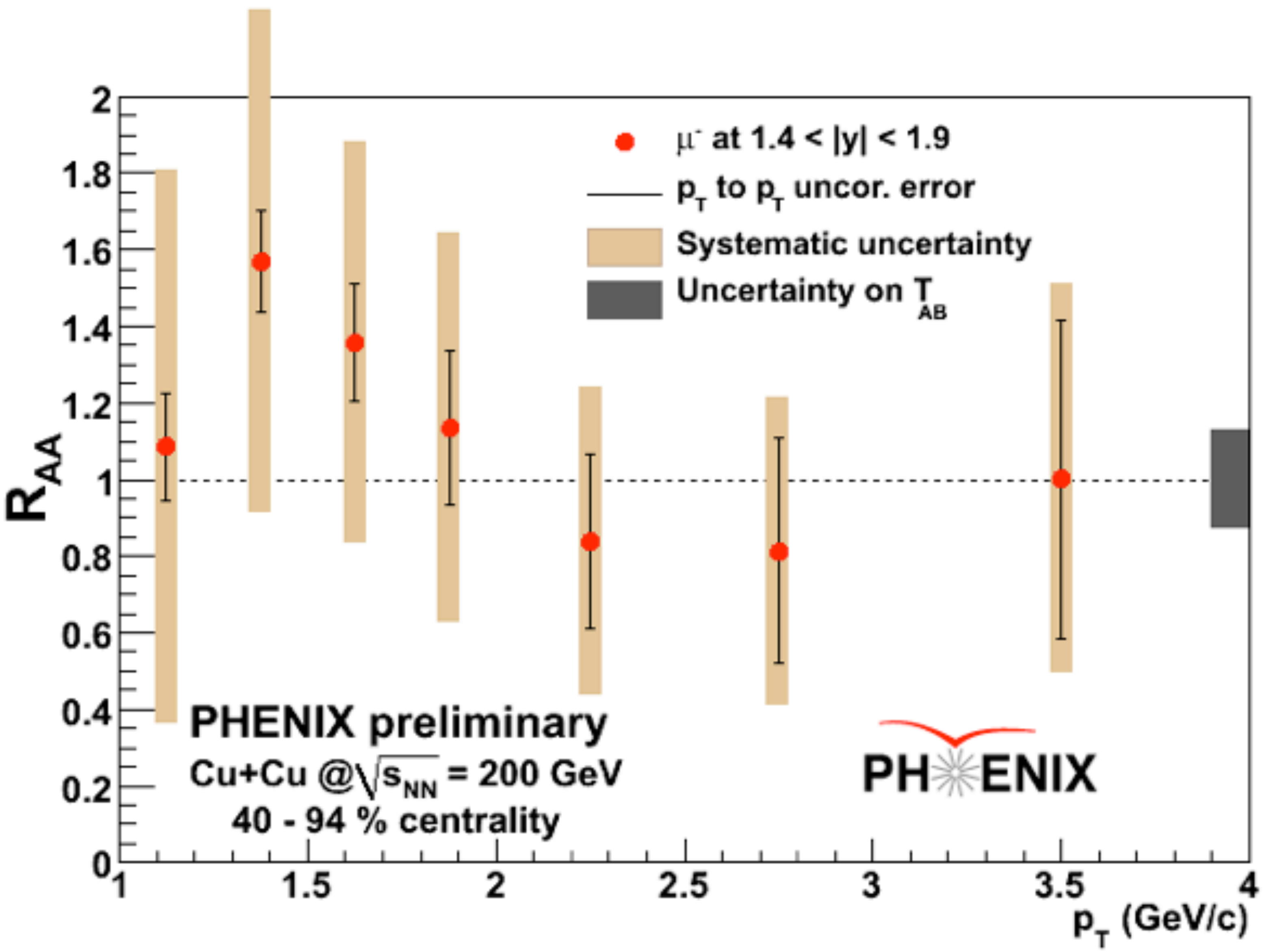


First measurement of (forward rapidity) HF muon spectra in heavy ion collisions

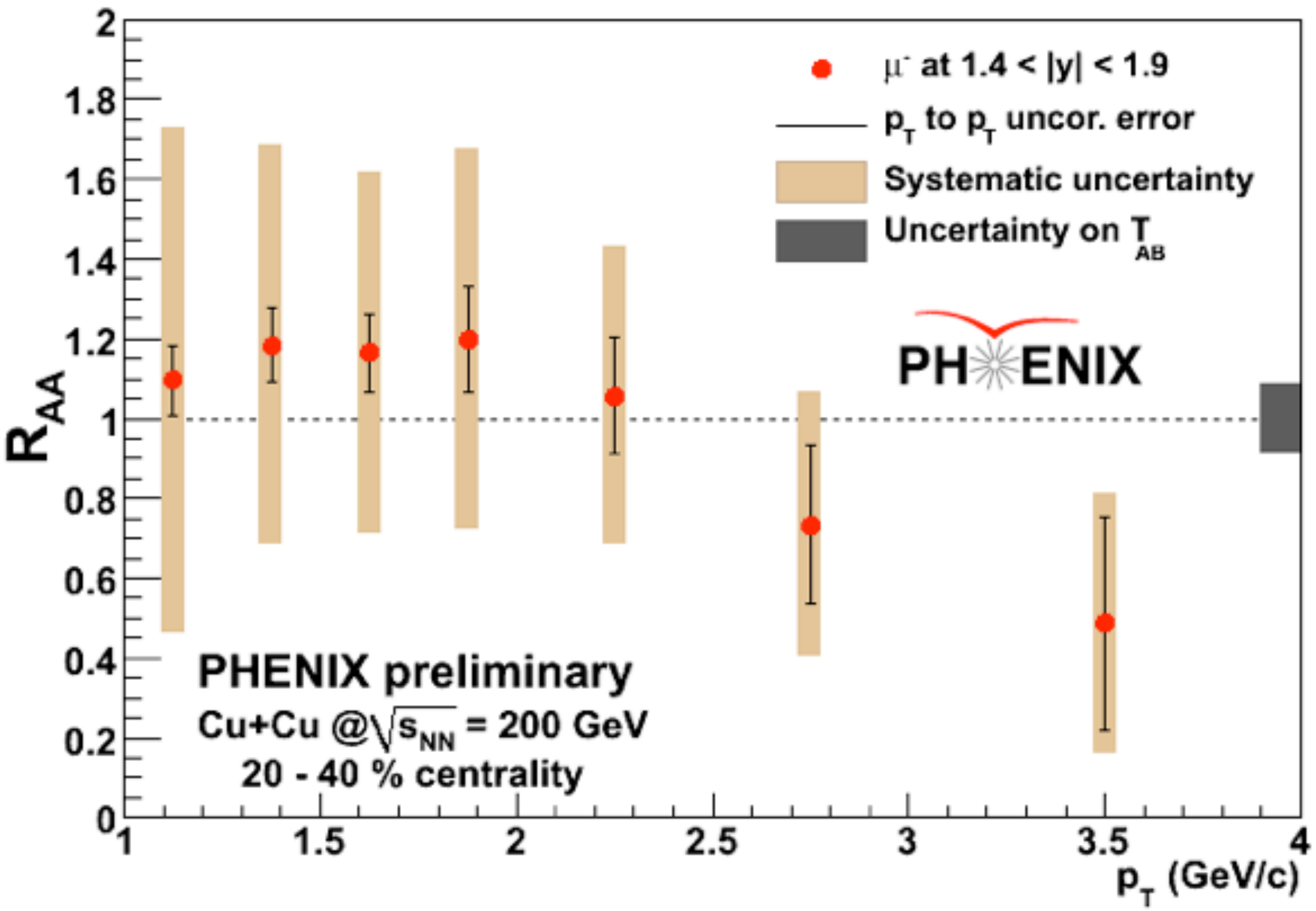
Cu+Cu centrality ranges: 0-20%, 20-40%, 40-94%

At higher p_T most central datapoints visibly lower than scaled p+p reference

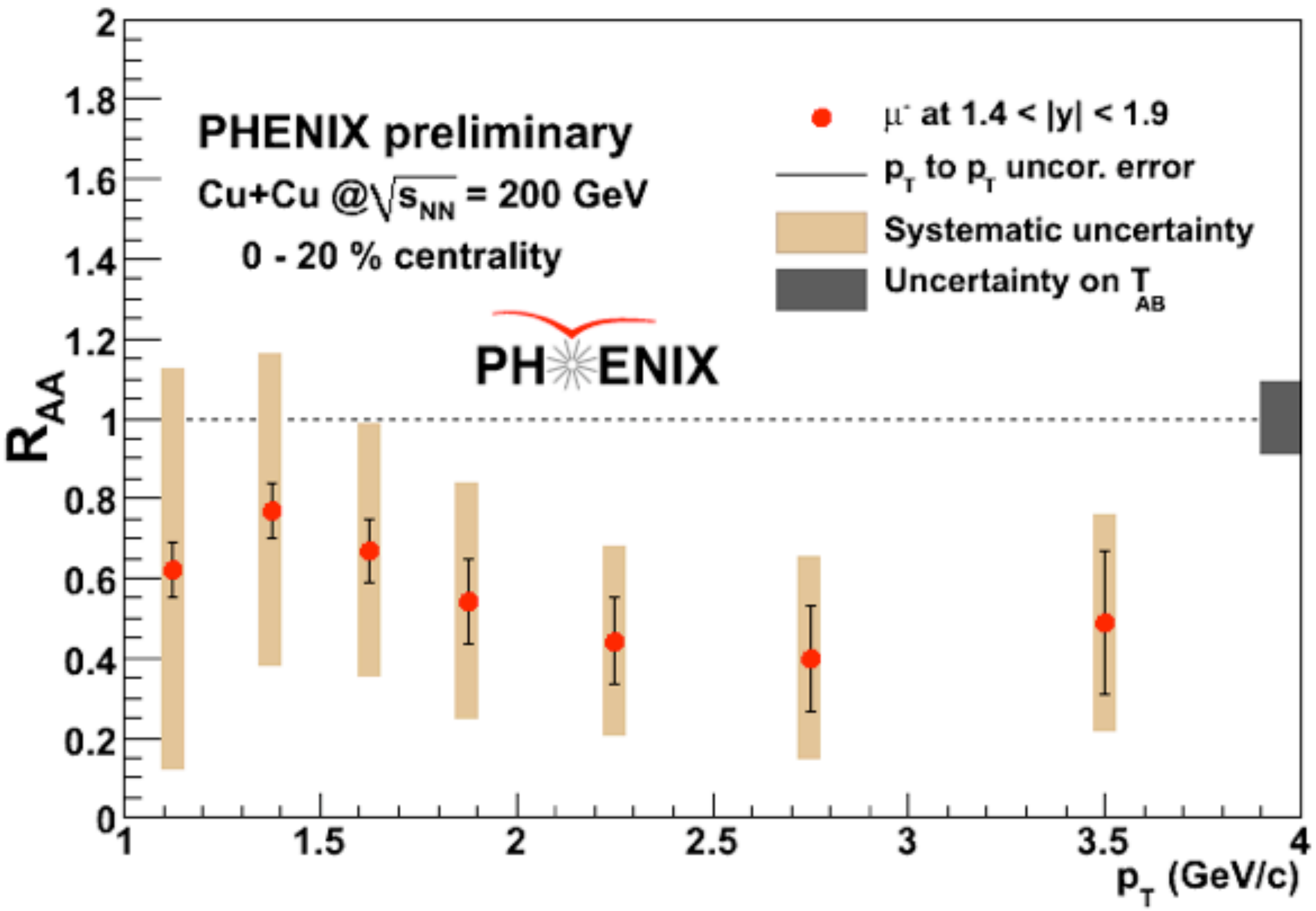
R_{AA} vs P_T in Cu+Cu collisions



R_{AA} vs P_T in Cu+Cu collisions



R_{AA} vs P_T in Cu+Cu collisions

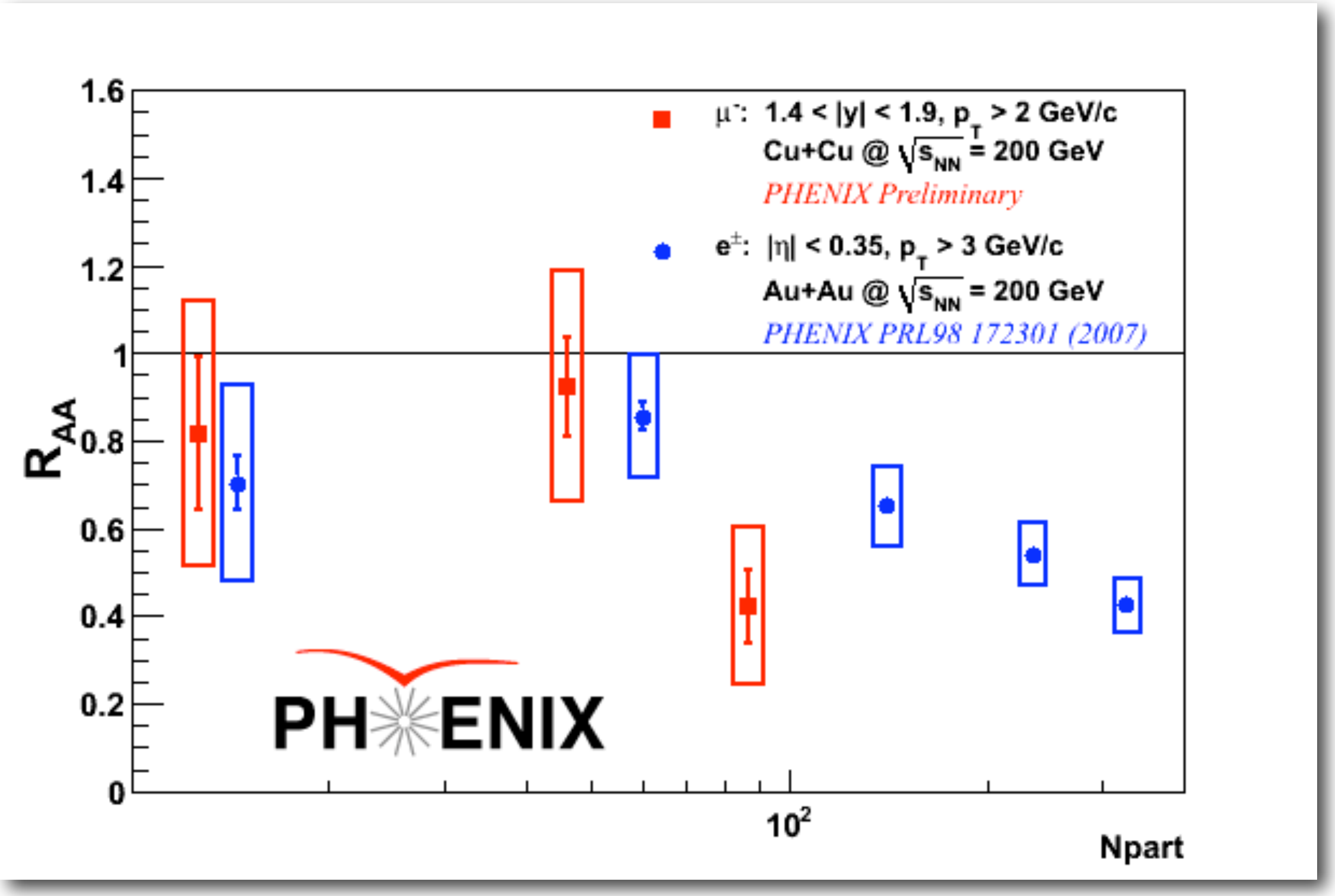


Large suppression of higher p_T heavy flavor muons in the most central Cu+Cu collisions

Final results expected to be submitted for publication within few months

Reduction of systematic errors needed. Expected after installing FVTX detector for Run-12

Heavy flavor muons vs. electrons at higher p_T



Warning! Not apples to apples comparison

Potentially larger HF muon suppression in Cu+Cu for N_{part} ~90 compared to naive projection from HF electron measurements in Au+Au

About the same level of suppression if comparing the most central electron datapoint to the most central muon datapoint

Trying to understand apples vs. oranges

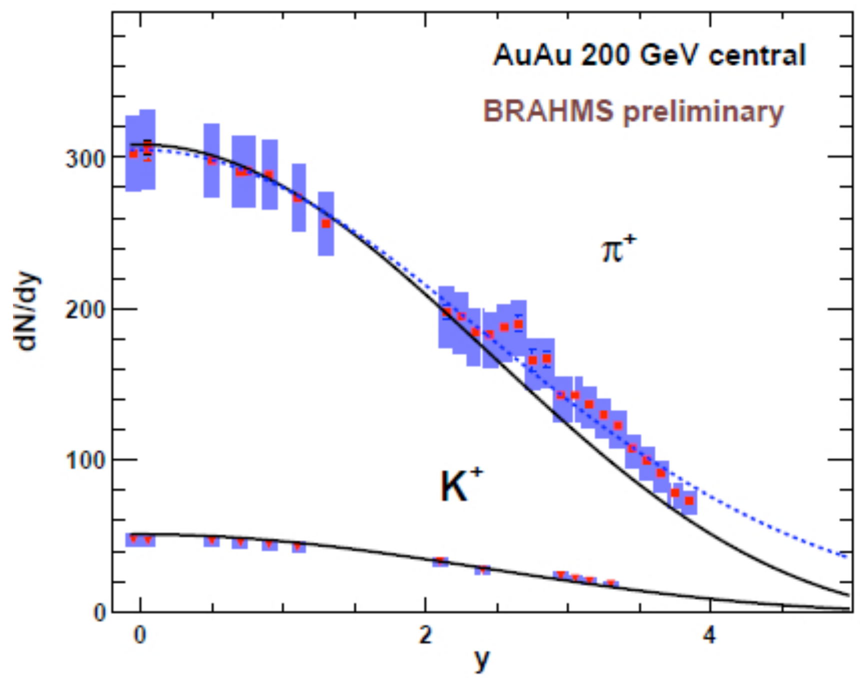
Central Cu+Cu vs. central Au+Au (same rapidity)

$$\frac{\varepsilon_{Bj}^{AuAu}}{\varepsilon_{Bj}^{CuCu}} = \frac{\left[\frac{\langle m_T\rangle}{\tau_0 A_T}\frac{dN}{dy}\right]^{AuAu}}{\left[\frac{\langle m_T\rangle}{\tau_0 A_T}\frac{dN}{dy}\right]^{CuCu}} \approx \frac{\left[\frac{dN}{dy}\right]^{AuAu}}{\left[\frac{dN}{dy}\right]^{CuCu}}\left(\frac{A^{Cu}}{A^{Au}}\right)^{2/3} \approx 1.8$$

Naively expectation suggest that heavy quarks see ~ 2 times less hot medium in Cu+Cu collisions in forward rapidity than in Au+Au collisions in mid-rapidity.

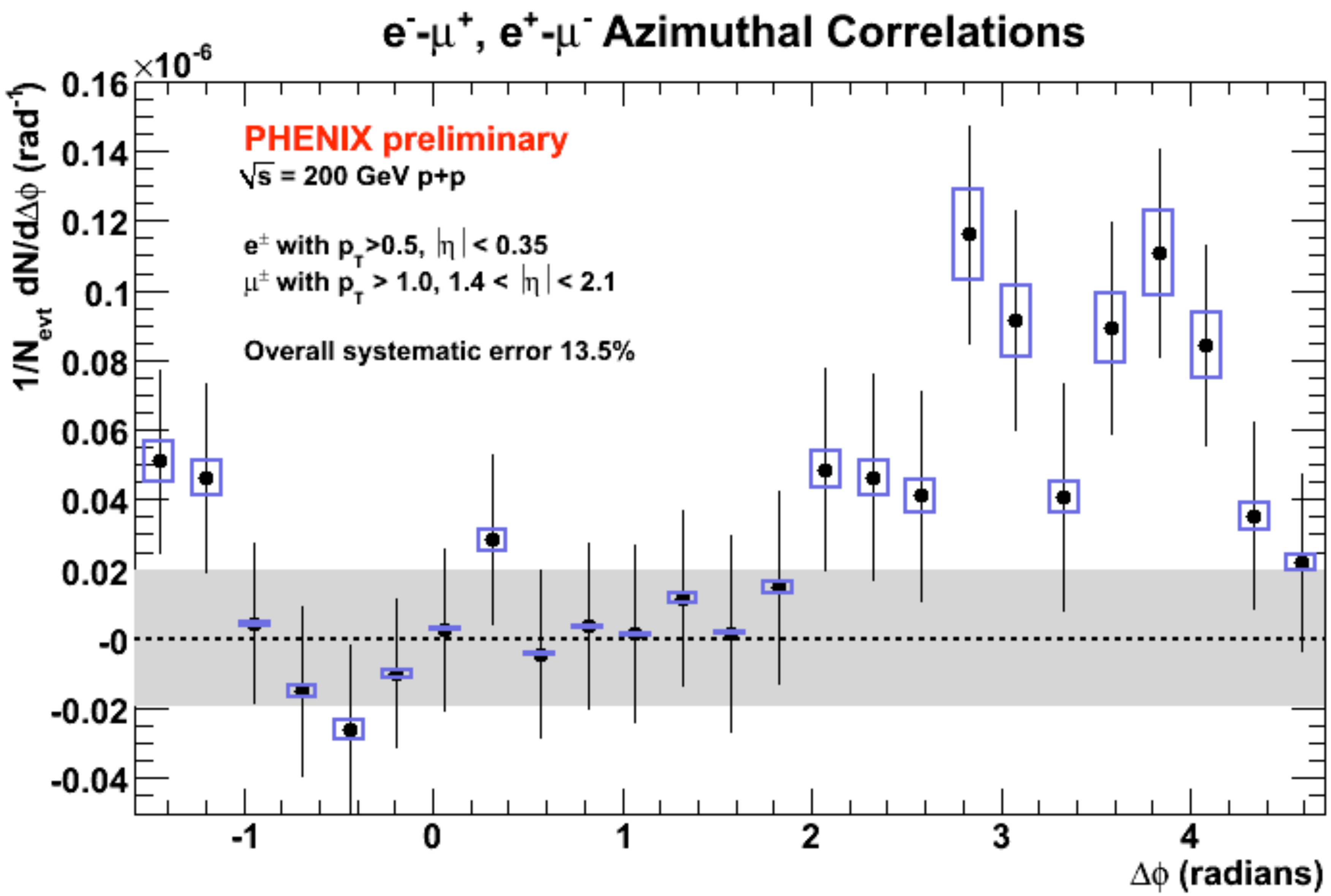
Yet the same level of suppression

dN/dy vs. y



Bjorken energy density for the collisions of same species expected to be about 20-25% different between y~0 and y~1.65

e-μ correlation



Invariant Yield 2.11e-07 ± 3.04e-08(stat.) ± 3.5e-08(sys.)

Summary

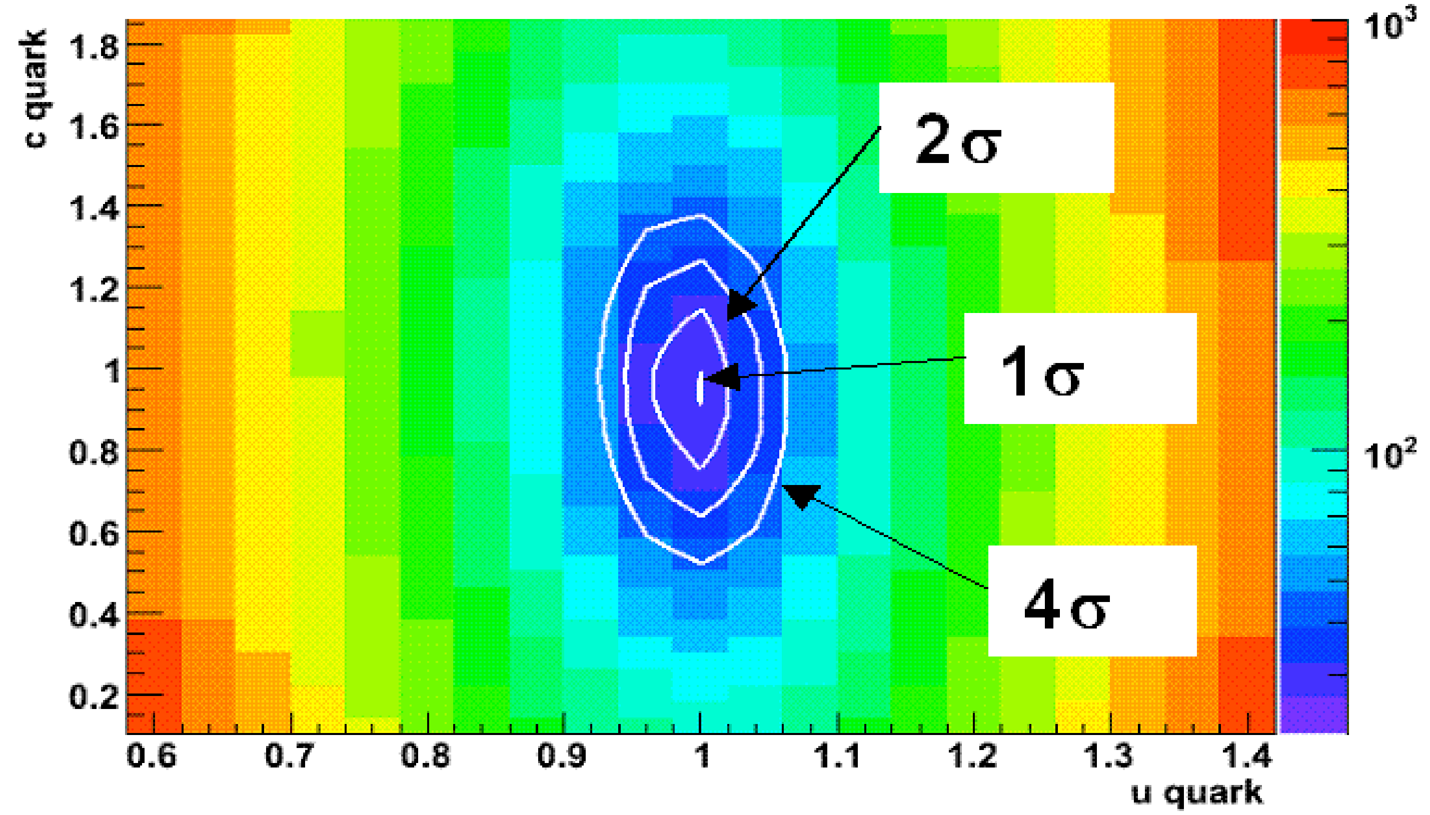
- Decade of variety of excellent measurements delivered by PHENIX
- Surprising results in open heavy flavor sector: Large suppression and collectivity
- Good progress on the theoretical side in qualitative understanding of possible in-medium effects
- Likely large cold nuclear matter effects in forward rapidity. Need some predictions here
- More precise (“direct”) measurement of open heavy flavor mesons with vertex detectors needed

Open heavy flavor outlook for PHENIX

- A list of “finalized” open heavy flavor measurements headed towards publication in the nearest future
- “New” analyses underway using high statistics datasets (p+p, d+Au, Au+Au) from the RHIC Runs 8, 9 & 10
- HBD detector installed during Runs 9 & 10: Expected additional sizable reduction in the electron background
- RHIC Run 11 underway. PHENIX taking first data with newly installed VTX detector. FVTX detector expected to be installed before Run 12

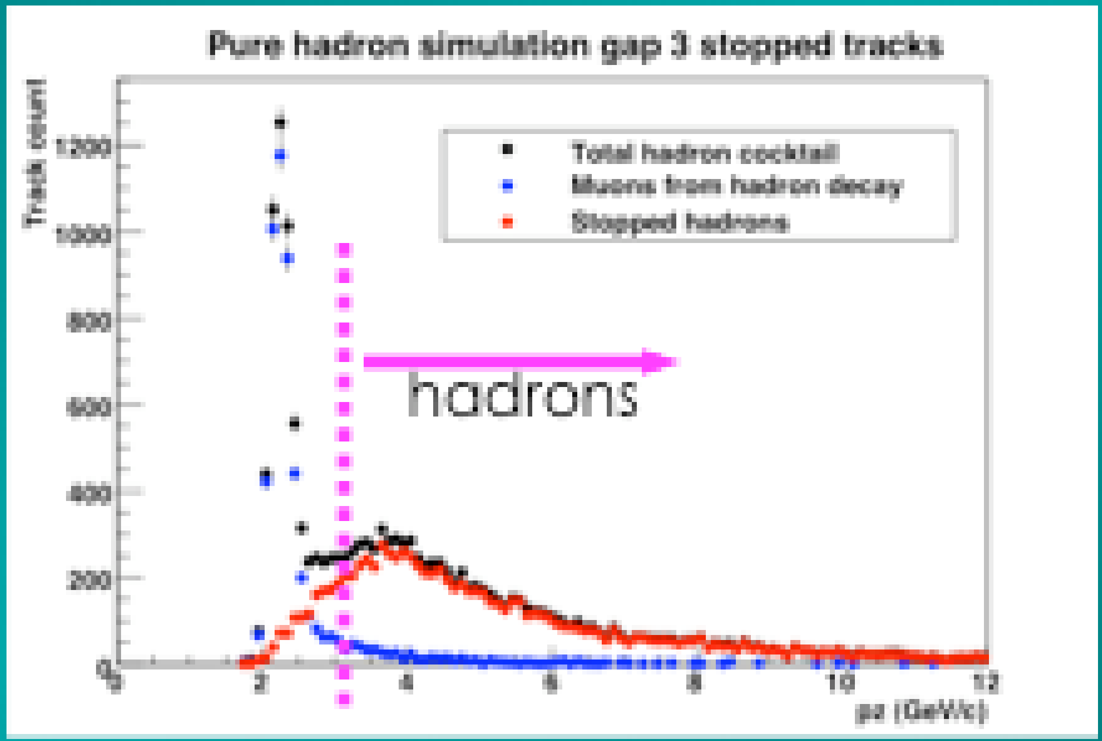
For details please see “*PHENIX Future Flavor Measurements*” by R. Noucier (BNL) on January 6 at 2:40 pm

Back up slides


c quark
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
u quark
10^3
10^2
2σ
1σ
4σ

Adjusting/tuning cocktail to match data

For muon/hadron separation, applying momentum cut on tracks that stop in gaps 2 & 3, keeping hadrons.



We "tune" cocktail by forcing simulated stopped hadron P_T spectra to match data at gap 3.

Finally, using additional data handles to check MC/data matching:

1) gap2 hadron spectra
2) Z vertex slope matching